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CONDITIONS OF FORMATION OF A WATER FILM
ON THE HIGHWAY AND ITS EXPULSION
OWING TO ACTION OF A TIRE

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**CASE FILE
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CONDITIONS OF FORMATION OF A WATER FILM ON THE
HIGHWAY AND ITS EXPULSION OWING TO ACTION OF A TIRE

J. Lefranc

ABSTRACT: Many works show that the traction of a tire decreases quickly when the thickness of the water film encountered by the tire tread during its movement increases. There is, on this account, some advantage in knowing well the orders of magnitude of the water thicknesses which are formed during a rain on such and such a highway or such and such an airport runway.

The development of a neutron probe allowed these measurements to be carried out with an accuracy better than 1/10 of a millimeter. In this way, water films of 1 - 2 mm (with the equivalent of a rain of 40 mm/hr) could be observed during their drainage down to 0.1 - 0.5 mm. These developments in time allowed a clear differentiation to be made between the draining capacities of two airport runways, one transversely grooved and the other conventional.

In reality, we have found that the various hydrodynamic modes can be depicted by one or several relations of the $H=a \cdot t^{-b}$ type which appear to be specific elements of the gradual development of film thickness as a thin flow.

Analysis with logarithmic coordinates allow precise judgments to be made as to the draining qualities of different surface textures and, for example, to examine more closely those selected to avoid aquaplaning on airport runways.

Introduction

/5*

The goal of record program 04-05-9 prepared at the Surface Characteristics Branch of the Highway Department envisages more particularly the study of the formation and drainage of water films on road surfaces. Within this scope we have found it appropriate to design one series of experiments in the laboratory and another very different series on the highway. The former series allows a systematic study of streaming since the parameters selected can be specified to the desired values whereas the latter series provides the capability for confirming in an operational environment such and such a circumstance of flow

In order to establish a procedure for carrying out these investigations on highways, we concentrated our efforts towards the determination of

* Numbers in the margin indicate pagination in the foreign text.

thicknesses of water film by deceleration of neutrons. In collaboration with the Branch for Application of Isotopes, an apparatus was therefore designed according to this principle, then calibrated in the laboratory for different heights of water and types of surface. There still remained, however, the requirement for studying the flexibility of use and effective accuracy of this equipment in an operational environment.

The application to airport runways turned out to be very advantageous since the great lengths of flow which can be present across runways lead to the formation of considerable water film. An almost total loss of traction can occur during a high speed landing. This danger largely justifies the interest in gaining a precise knowledge of water thicknesses.¹

The contacts made with this objective in mind with Mr. Lorin, Divisional Engineer of the T.P.E. (Travaux Publics de l'État, National Administration for Public Works) and Laboratory Manager at the Paris Airport have caused appearance, at the same time as the opportunity for such determinations of thicknesses of water film, of the requirement for pursuing the matter still further. Indeed, Mr. Lorin directed the carrying out of comparisons between transversely grooved and non-grooved runways based on the friction coefficient criterion measured by means of the stradograph of the CEBTP. The increase of this coefficient as a function of time elapsed after end of the rain is relatively greater in the case of grooved concrete as can be ascertained by comparison of the curves of Figure 1. This difference in behavior has been attributed to a swifter drainage favored by grooving. Furthermore, the merely visual examination of the two surfaces at various instants of drainage appears to confirm this viewpoint (photos 1 and 2).² /6

1. A recent report (NASA 1968) notes the fact that, out of the total of aircraft accidents, there is a percentage of 35% attributed to accidents owing to losses of traction (of which 14.6% in aquaplaning condition, 10.8% with viscous slippage, 9.7% in presence of snow or ice).

2. These documents were kindly passed on to us by Mr. Lorin. Photos 1 and 2 correspond to one of the first grooving tests (distance between axes: 30 cm) since abandoned in behalf of grooves 10 cm apart.

The question therefore became one not only of measuring thicknesses /6 of water in permanent flow or in a state of interception (residual water) but even of computing the drainage rate.

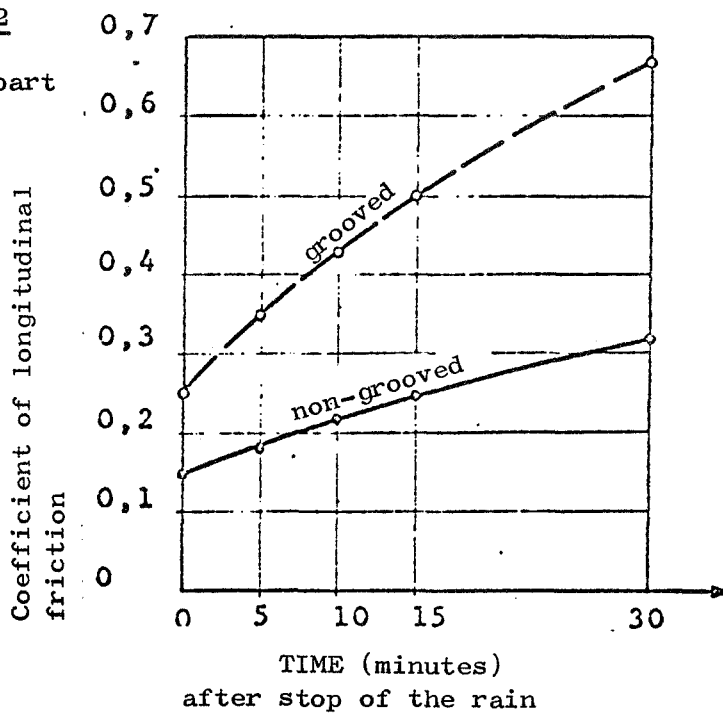
Several series of experiments were therefore organized in collaboration with Mr. Lorin and Mr. Chanut who supplied us with water and took care of safety questions with regard to the Airport control tower.

These various tests form the subject of the present report.

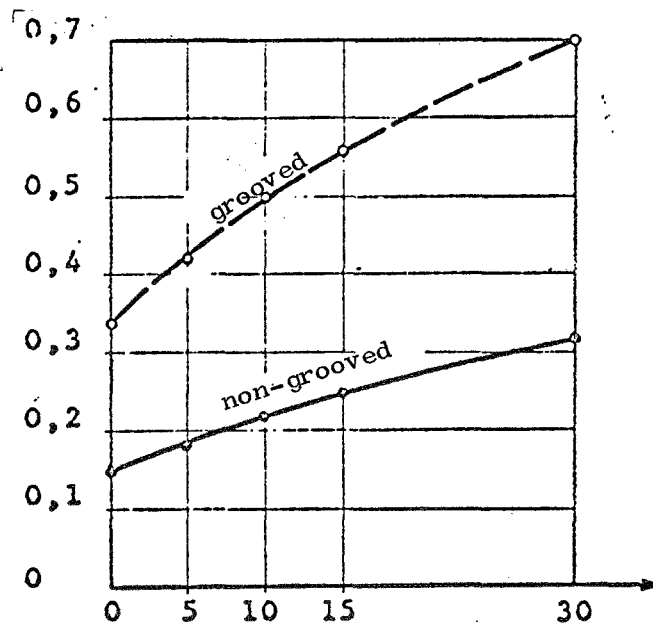
We shall first of all specify the terminology traditionally characteristic of the various phases of flow, then we shall summarize some laboratory findings which will be used subsequently. Finally, we shall provide a cursory description of the neutron measurement devices as well as a report of the experiments. The conclusions which are to be drawn from the above will logically follow.

Track no. 22
Channels 10 cm apart

/7

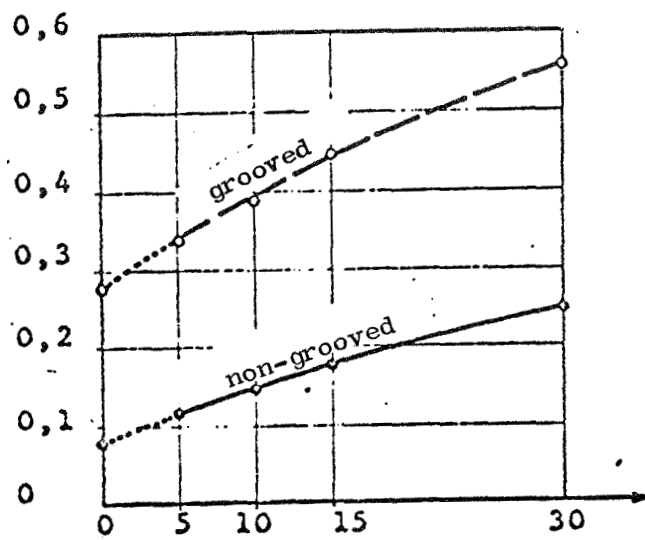


Track no. 22
Channels 5 cm apart



Track no. 47

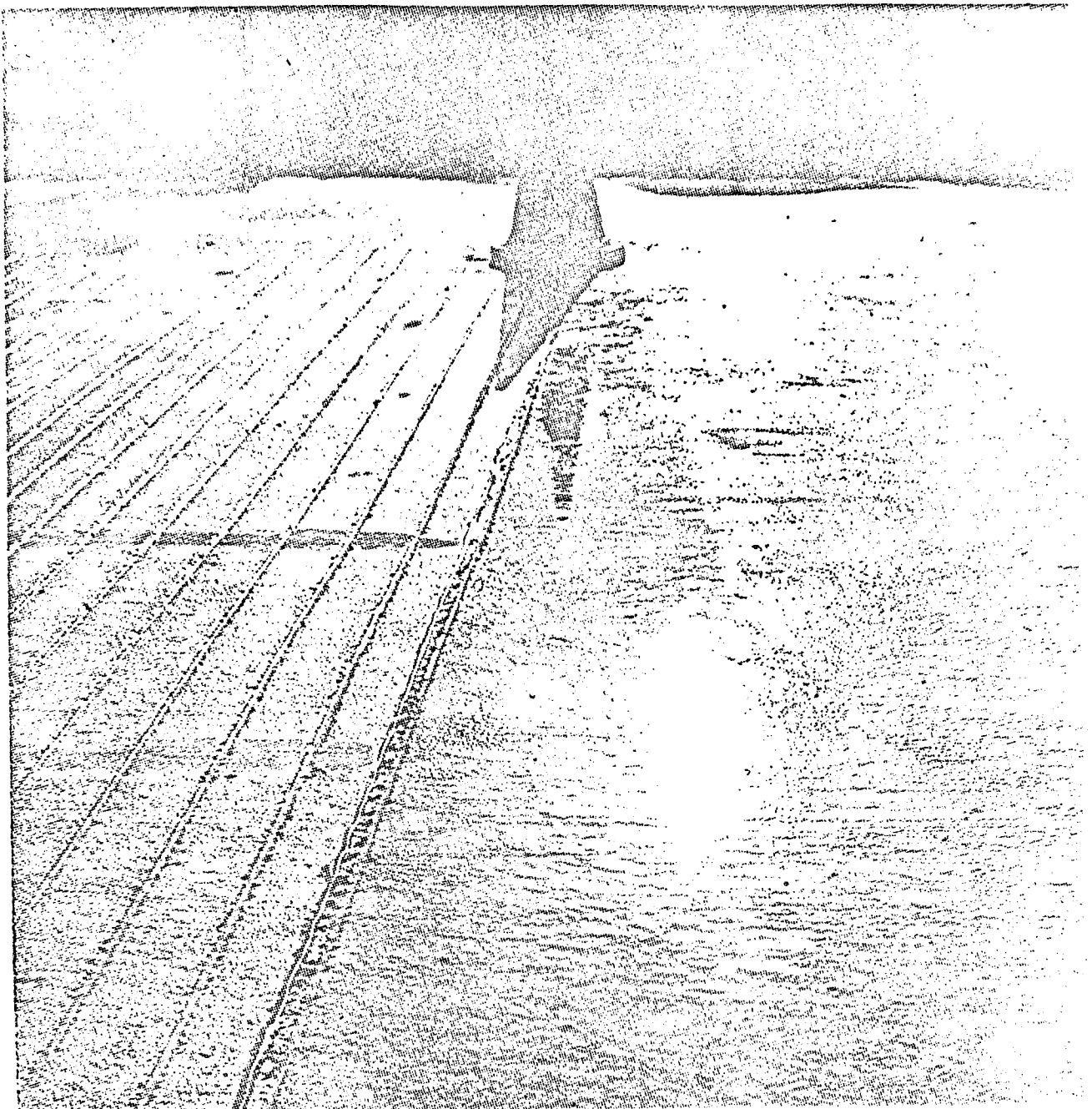
Channels 10 cm apart



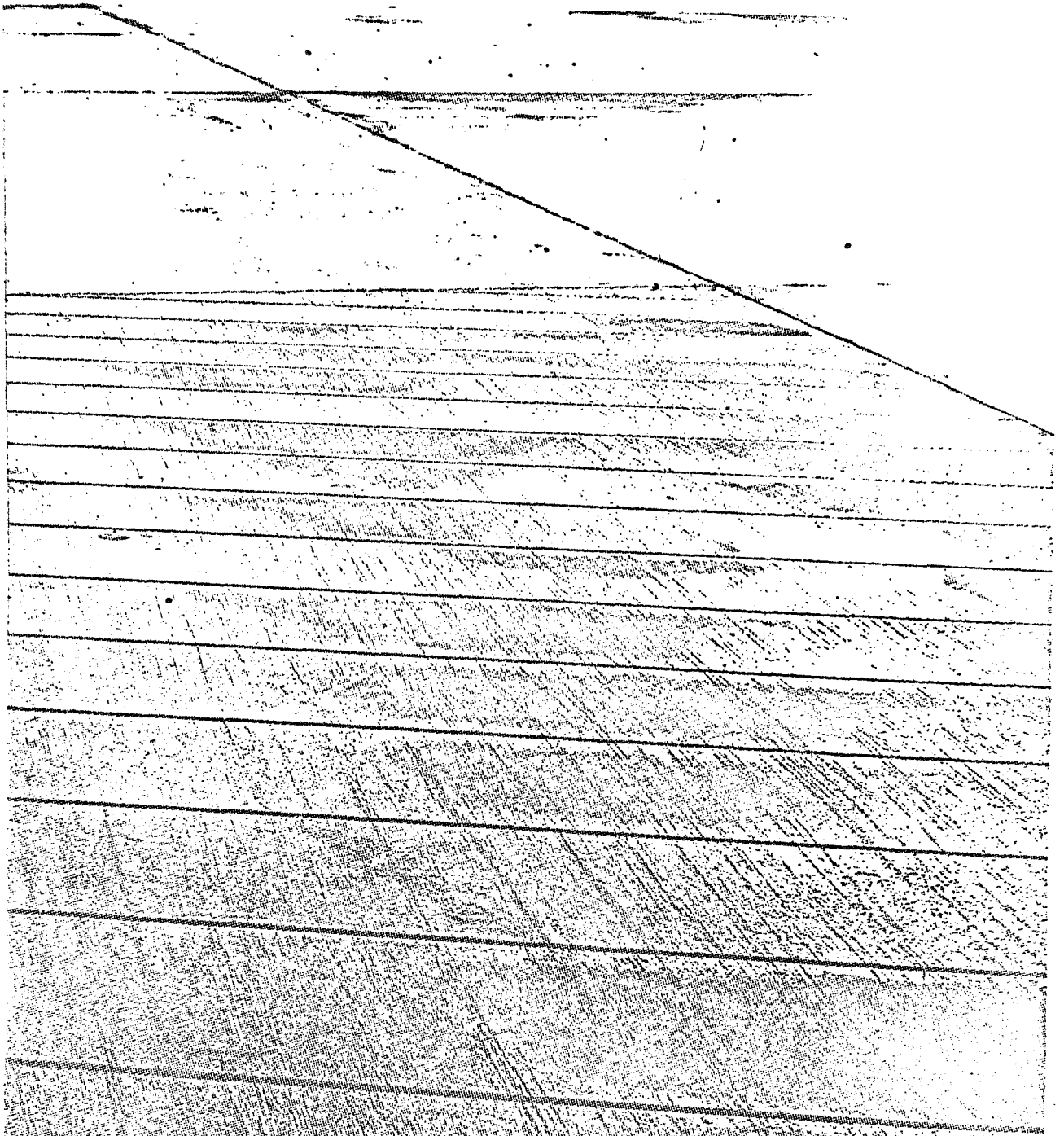
7

COMPARISON OF DRAINAGE ON GROOVED AND NON-GROOVED CONCRETE

On the left, on the grooved concrete, the roughness is already obvious whereas the non-grooved concrete still remains immersed by a thin water film. On the right of the photo, the existence of this water film explains the abrupt stoppage of the tire tracks left by the Stradograph on the grooved concrete.



QUICKER DRYING OF A GROOVED CONCRETE



The weight variations of a platform supporting an artificial surface of the road surface type allow, when the latter is sprayed, plotting of a typical concentration - recession curve (Figure 2).

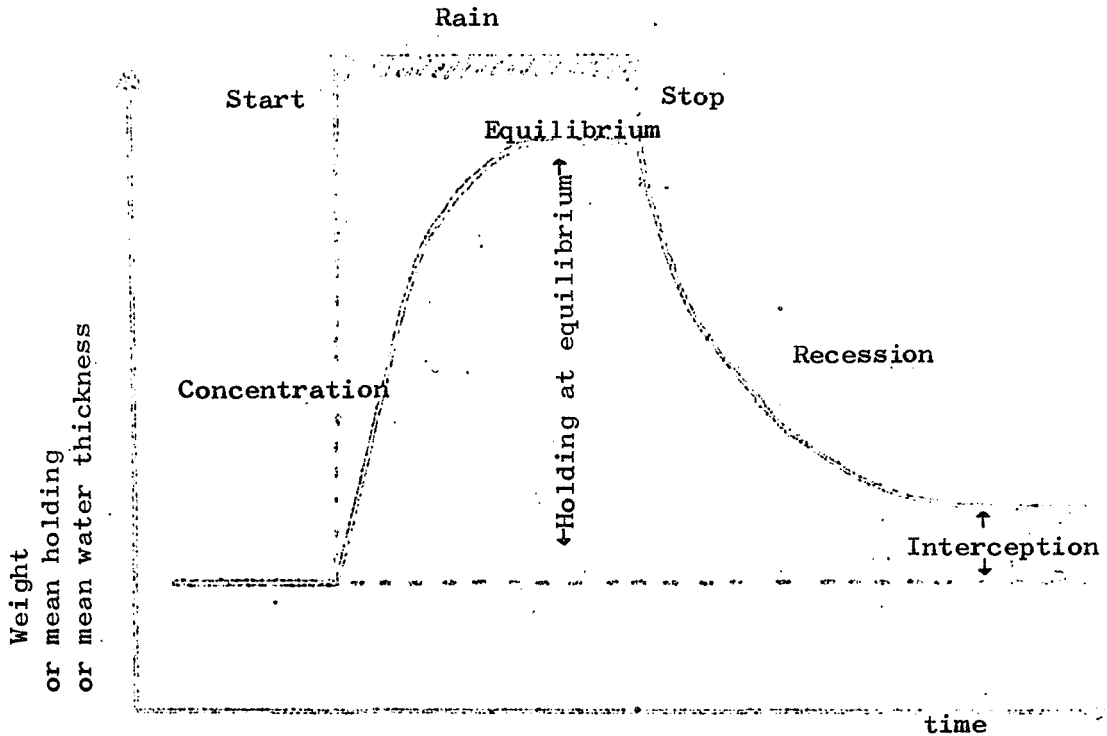


Diagram of a hydrogram and related terminology

Figure 2

3. LEFRANC (1969)
Cf. References on p. 56 for names and dates.

While the rain is falling and when the permanent operating mode is /11 set up, the quantity of water present on the surface is called "holding at equilibrium." As soon as the rain stops, the water film becomes thinner since the run-off at the edge continues to occur. This is the recession mode, or reduction of the "holding" which more or less quickly will result in a new equilibrium characterized by the volume of water trapped by the surface depressions, called residual water.

Various writers have provided different expressions for description of the recession. For example, Izzard (1946) indicated the sheet of water by:

$$h = k l^{0.33} \quad \begin{aligned} h &= \text{film thickness (foot)} \\ l &= \text{length of flow} \\ k &= 4/3 (i/43,200)^{0.5} \left(\frac{0.0007 \text{ in}}{s} \right)^{0.33} \quad (1) \\ s &= \text{slope, } c: \text{ coefficient of roughness (cement } c = 0.012) \\ i &= \text{rain intensity (mm/hr)} \end{aligned}$$

and described recession by the function:

$$t_r = \frac{D_o F(r)}{60 q_e} \quad \begin{aligned} t_r &= \text{time required in recession} \\ r &= \frac{q}{q_e} \quad (2) \\ \frac{q}{q_e} &= \text{ratio of flows} \\ F(r) &= 0.5 (r^{-2/3} - 1) \\ D_o &= \text{\# holding at equilibrium} \end{aligned}$$

at instant t_r and at equilibrium

On the other hand, Hicks (1946) prefers a function of the type: /12

$$q = K e^{-at} \quad \begin{aligned} q &= \text{flow at edge} \\ t &= \text{time} \quad (3) \\ a, K &= \text{numerical coefficients} \end{aligned}$$

Note that residual water does not enter into these descriptions of drainage.

During the experiments carried out at the Central Laboratory of Civil Engineering, the recession mode was observed and, in contrast to the preceding results, we found a linear log-log relationship between the variation of weight p of the film, i.e. the flow and the time, or:

$$\log \frac{\Delta p}{\Delta t} = a_0 - b_0 \log t \quad a_0, b_0 = \text{numerical coefficients} \quad (4)$$

Since the flow at the edge is equal to the variation of the water film:

$$q = \frac{\Delta p}{\Delta t}$$

and the latter is proportional to the mean height \bar{h} of the water on streambed area S :

$$p = S \cdot \bar{h}$$

it follows successively

$$q = \frac{dp}{dt} = S \cdot \frac{d\bar{h}}{dt} = A t^{-b} \quad (5)$$

A, B : numerical coefficients

One example of recessions recorded with plate G 14, made from Givet's /13 limestone granulated material and having a depth to sand of $HS = 2$ mm for the 1 and 15% slopes, after a rain of 365 mm/hr, is provided by figure 3 (computational details are given in annex I). A good agreement with linearity can be observed. It is therefore this rule (5) which we shall use as guide in the study of the drainage of the water film on the cement runway.

permanent flow 5,8 g/s

/14

1

flow g/s

Surface G1.4

Intensity of rain 365mm/hr

Slope 1 and 15%

10^{-1} Width at the edge 20 cm

Length of flow 30 cm

1%

15%

10^{-2}

FLOW IN RECESSION

Fig: 3

time(s)

10^2

10

In order to confirm and supplement laboratory experimentation we have sought a quick and accurate means for characterizing water films and their development on surfaces of the road type.

The measurement of flows at the edge is extremely awkward since it requires placing the measurement system on a level lower than the edge, adds on additional delays as well as an artificial storage in the piping leading from the measurement device which is itself customarily not overly precise.

The measurement of water thicknesses therefore remains. The methods calling upon depth gauges are extremely fast but have serious disadvantages. Indeed, these gauges, already in use at the Road Research Laboratory and at the Central Laboratory of Civil Engineering, disregard owing to their design the quantities of water located below the head of the granulated material. Now, in the case of the customary rainy conditions prevalent at our latitudes, the precipitations are rarely violent but long in duration and it has often been observed that flow takes place in most cases following a path between the granulated material with the sharp edges only disappearing under the water film at time of heavy rains which are rare and of short duration or when the surfaces have a shallow texture which latter condition is generally avoided.

The peak water level gauge (limnometer) provides very precise but detailed values and in order to have a system profile of the flow, i.e. a mean thickness over a domain included several granulated materials, it is necessary to take a great many measurements and process them statistically.

We took into consideration in this case a method calling upon nuclear /16 radiation and, in close collaboration with the Isotopes Application Branch, we decided upon a course of research, the deceleration of high-speed neutrons and specification of calibrations which appeared necessary to us.

4. An investigation is being carried on prior to filing a Patent Application.

The prototype apparatus, completely designed and tested by the Isotopes Application Branch is shown on photos 3 and 4. The principle consists in the installation (Figure 4) of two 50 mci sources of Americium - Beryllium, generators of high-speed neutrons and four boron trifluoride slow neutron counters, in a paraffin block of a size such that the emitted neutrons will be made very slightly epithermal. They will in this way have the greatest of opportunities to be sufficiently slowed down by the thin water film and then be counted in the state of thermal neutrons.⁵ /16

The presence of water (or hydrogenated substance such as asphalt⁶) consequently increases the computation. The differences between a dry computation and others carried out in the presence of water films provide data varying as the mean quantity of water located under the apparatus.

It is possible to consider that the various calibrations set up with many materials of varying natures and roughnesses provide a single straight line for which it is true that: 450 cpm/0.1 mm (fig. 5). The accuracy corresponding to this only choice can be calculated to ± 0.1 mm in the domain considered (0 - 4 mm). This accuracy could be improved by increasing the sensitivity of the apparatus, although it could nevertheless be seen that the present accuracy already reaches 1/100 of a gram per cm² or one drop of water per 5 cm² which appears amply satisfactory. /20

5. Baron (1969) and Bulletin de Liaison.

6. Indeed, the hydrogen atoms have one of the strongest deceleration coefficients (cf. bibliography: Bulletin de Liaison)

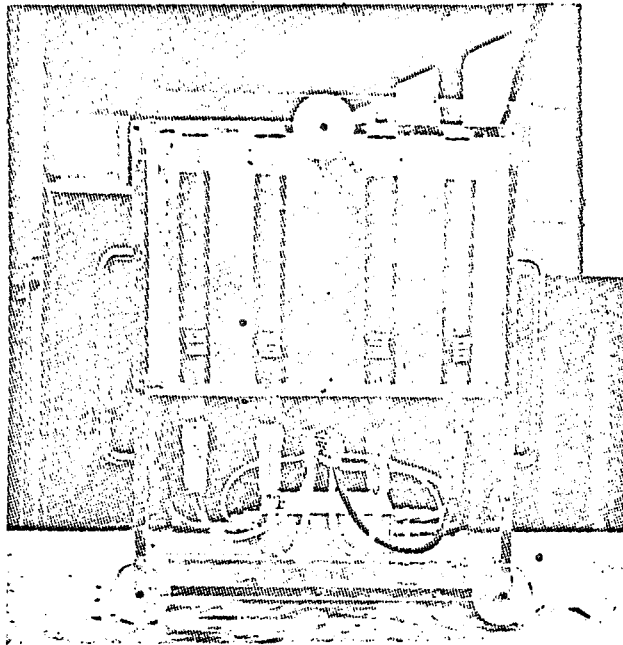


PHOTO 3

/17

View from the bottom

APPARATUS FOR MEASUREMENT OF THICKNESSES OF WATER FILM BY DECELERATION OF
HIGH-SPEED NEUTRONS⁷

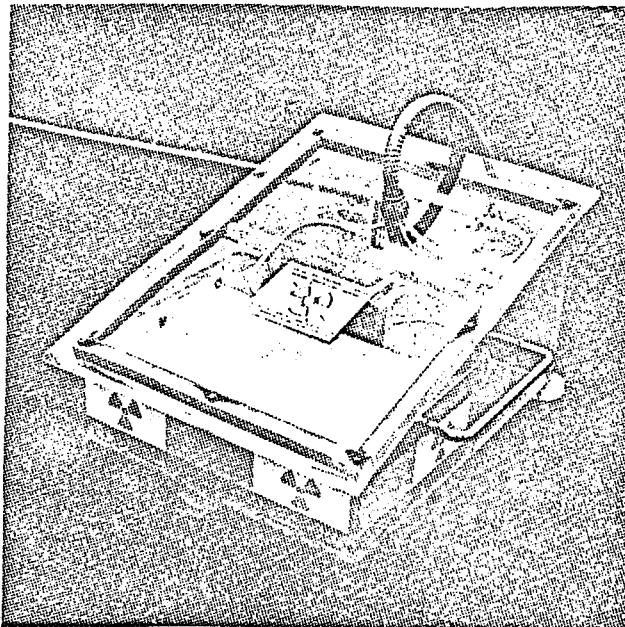


PHOTO 4

View from above

7. Bulletin de Liaison (cf. bibliography)

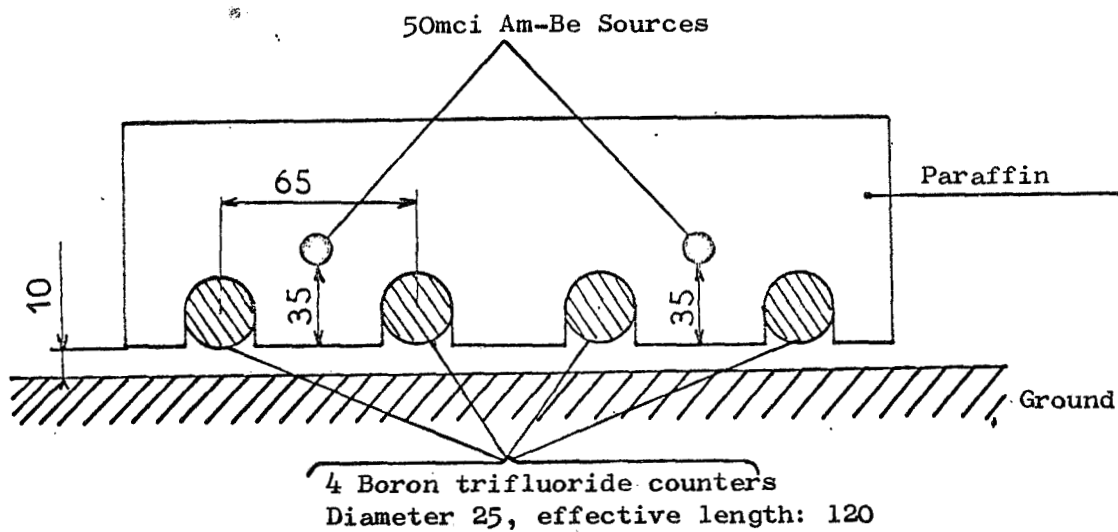
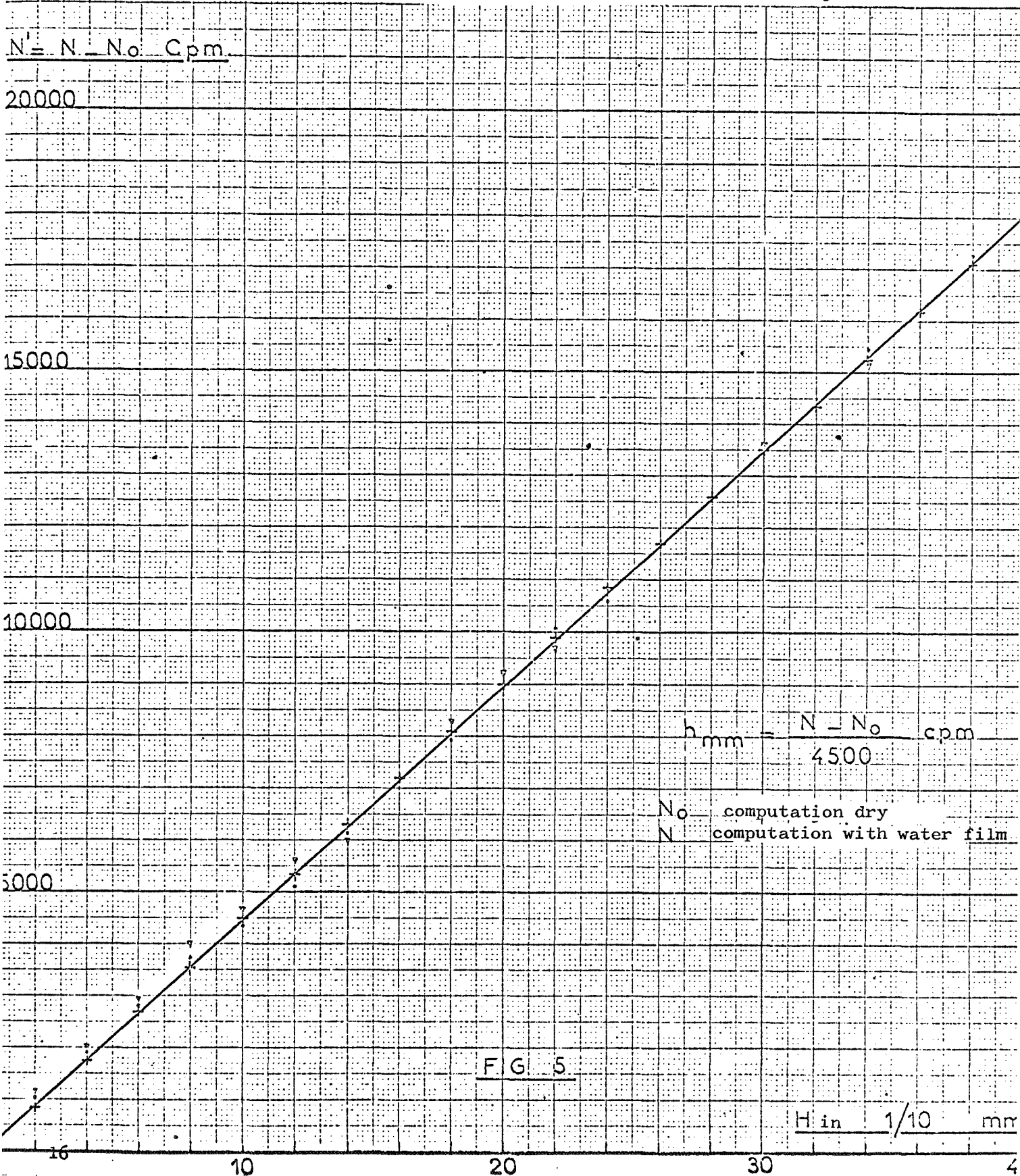


Figure 4

Variation of the computation as a function of the water height



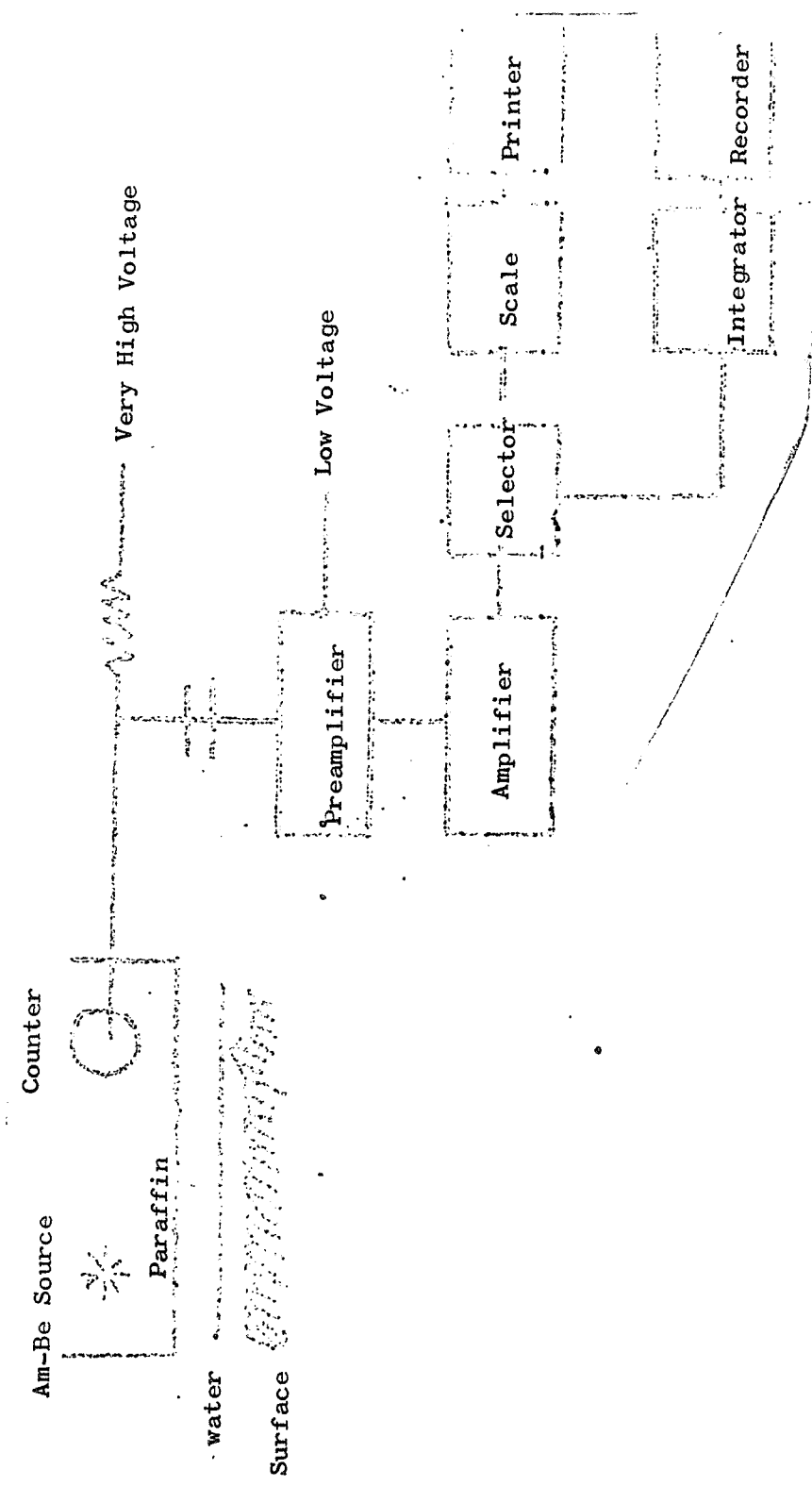


Figure 6

MEASUREMENT OF THICKNESSES OF WATER FILM

SYSTEM DIAGRAM

In addition to the good precision and accuracy of the apparatus, the great advantage can be found in the producing, in the case of the water thickness, a mean value over an area (40 X 40 cm) which can be considered as exact on the scale of the highway but large with respect to the sizes of the granulated material.

In addition, it is clearly possible to measure the mean thickness of the water located below the crest of the sharp points of the material and this is indeed the only practical way of carrying out this determination.

The apparatus is supplied with high voltage and carefully made leak-proof. By using an amplifier the counts are posted on a Baird Atomic scale, model 530, then printed out (Baird Atomic printer) and simultaneously compiled by an integrator (ILP 10 SRAT) and recorded (ESTERLINE ANGUS).

Guided and familiarized with surface flows by experimentation in the laboratory, provided with an apparatus for measurement of water thicknesses by the Isotopes Applications Branch, we were able to set up with Messrs Lorin and Chanut a series of experiments on traffic runway no. 47. This first test allowed us to learn the characteristics of the site and test the equipments. Later experiments were progressively modified as a function of successive critical reviews. The whole series of measurements were stretched out between 11 February and 8 April 1969 for it was necessary to satisfy several requirements on a simultaneous basis. The latter involved non-utilization of the runway, low wind velocity and absence of rain.

3.1 The site

The lots selected were located side by side (fig. 6a) on traffic runway no. 47, one being grooved and both having a longitudinal finish with jute cloth.⁸

The common transverse slope is 1% and the flow length is 18 meters.

On the lots tested, the depth to sand varies from 0.17 to 0.26 or 0.21 on the average to the exclusion of the grooves themselves. The grooves which are 10 cm apart are sometimes well cut out (photo 5a) and sometimes have deteriorated edges (photo 5b). The base is always perfectly polished by the diamond saw. The longitudinal gaskets made from rubbery material form two light impediments to flow both for the grooved lot as well as for the other. Let us summarize the geometrical characteristics of the site (fig. 6a):

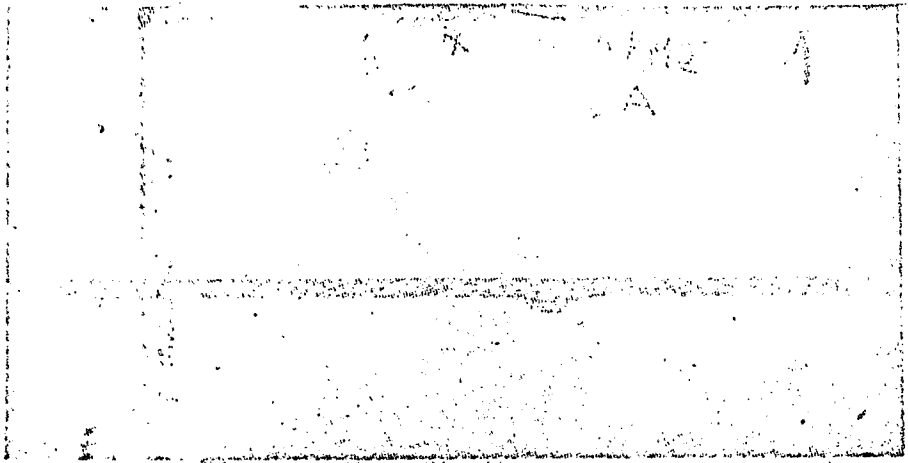
Common to both lots	length	18 m
	slope	1%
	depth to sand	0.21 on the average

8. Dalles, 135, 136, 137

GROOVE PROFILES

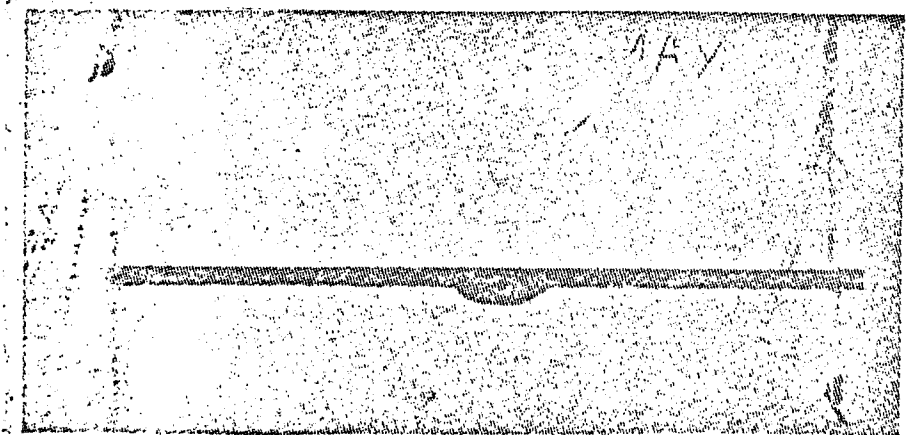
/22

PHOTO 5a



grooves in good
condition

PHOTO 5b

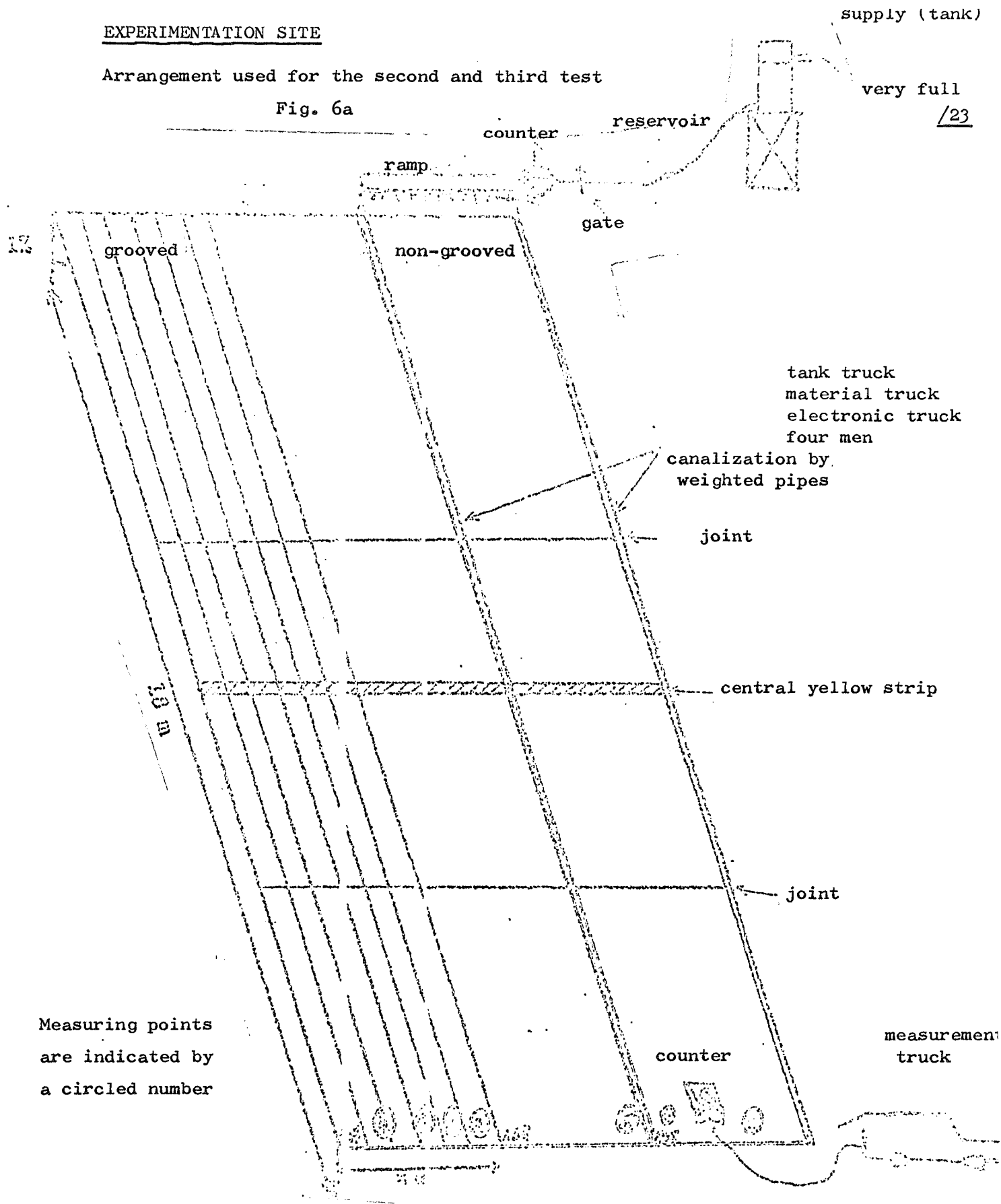


deteriorated
grooves

EXPERIMENTATION SITE

Arrangement used for the second and third test

Fig. 6a



Grooved lot	grooving	depth	5 mm
		width	8 to 12 mm
		distance	100 mm

/24

3.2 First test

The very day of this first experiment there were prevalent on the site conditions which turned out to be rather unfavorable: low temperature (3°), not inconsiderable cross wind (6 to 8 knots or 0.3 to 0.4 m/s). In addition, the spraying was done with a nozzle (photos 6 and 7) and it was not possible to set up a permanent streaming condition. It was nevertheless possible to plot recession curves at two points on the edge and two points at mid-slope as depicted respectively by figures 8-9 and 10-11 as taken from the printer data.

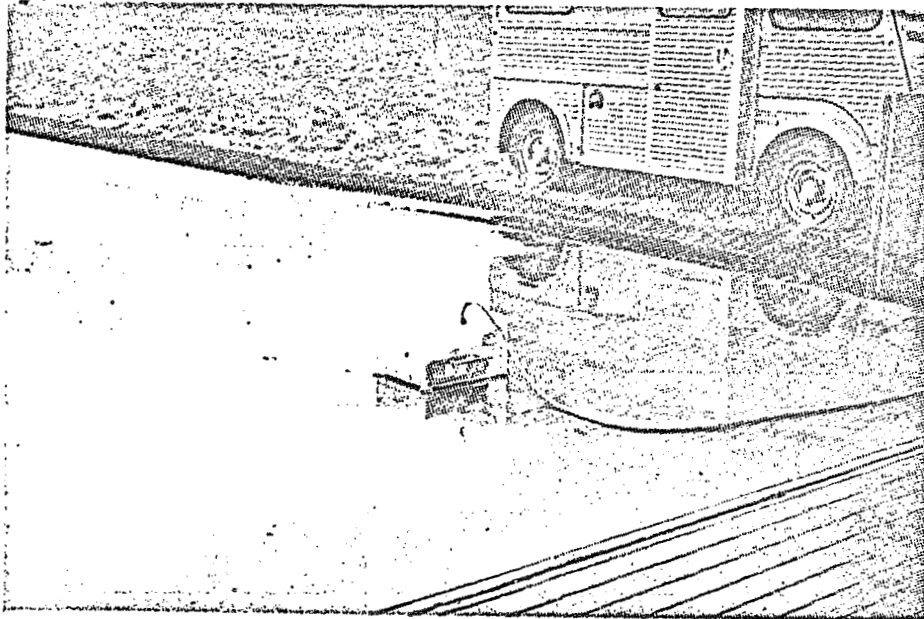
Curves (9) (10) correspond to the grooved surface, curves (8) (9) to measurements carried out at mid-slope.

The peaks produced reflect the absence of a permanent mode and their different heights come from the water thickness which varies with the pressure of the water in the tank, cross wind and deflects in uniformity.

Under these conditions, any exploitation became absurd.

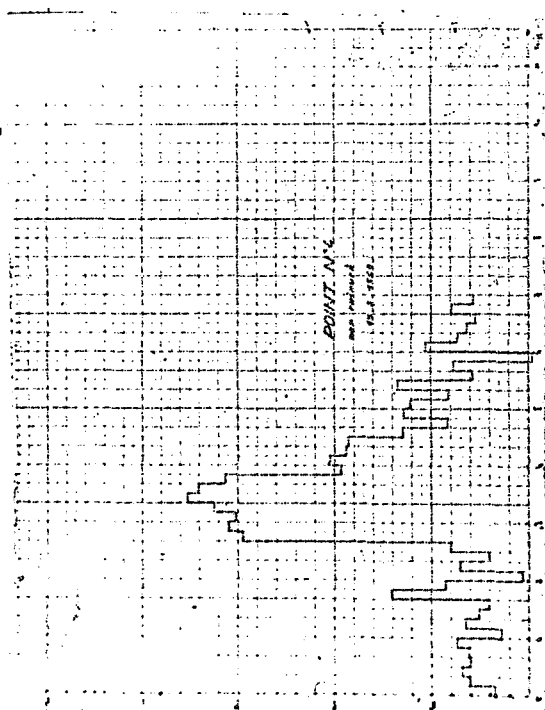


First test: nozzle spraying and defects in uniformity



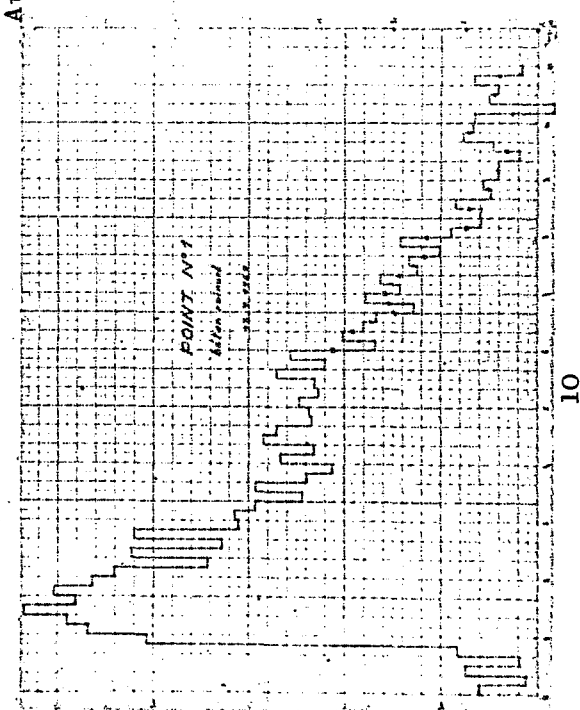
FIGURES 8 through 11

First test: Computation as a function of time

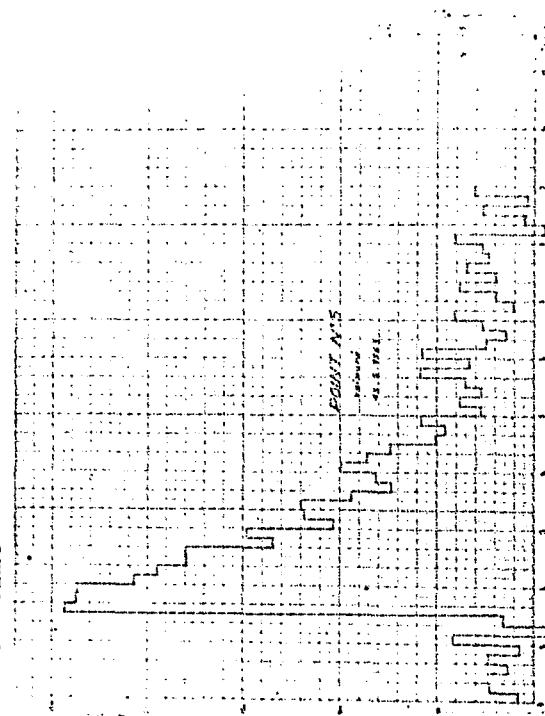


Non-grooved

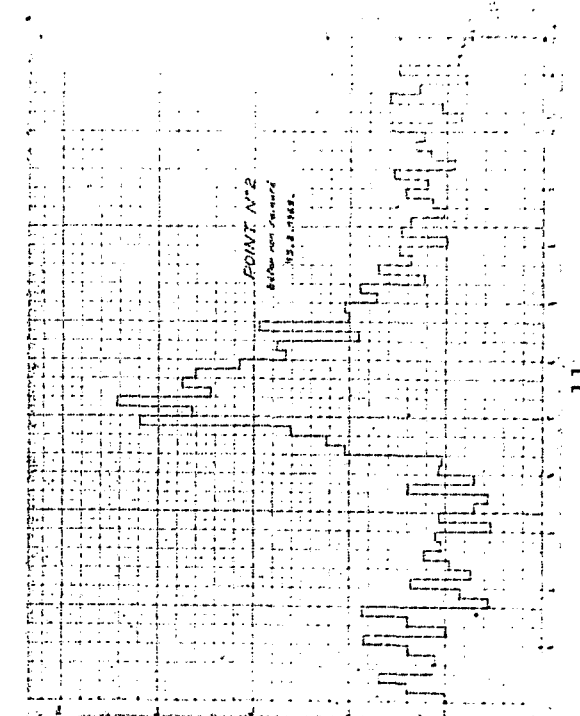
At mid-slope



At the edge



Grooved



3.3 Second test

/27

In order to obtain thicknesses of water which are stable and mutually comparable for permanent streaming conditions, each lot tested was laterally demarcated by a weighted tubing and spraying was produced by a ramp (diameter 30 mm) pierced with holes (3mm) which are 10 cm apart. The ramp was itself supplied by a very simple overflow basin system delivering a constant flow at a rate of 38 - 40 l/min. The width sprayed was approximately 3 m (width of lot).

The device used is shown in photos as well as in Figure 6a.

The measurement points were all selected at the edge at the same time avoiding defects in uniformity. The number of experiments carried out was limited to three by a violent wind which came up at the end of the morning.

The computational curves are shown on figures (12, 13, 14). There can be seen the long stabilization produced in the permanent mode for the measurement carried out on point 1. Subsequently, a shorter streaming to equilibrium was believed enough. The continuous curves are plotted by means of points representing the means of computations with 100 s. The drainage rates are mutually comparable except for the appearance of an unexplained "hump" on the curve relating to the non-grooved lot (fig. 14).

The satisfactory experimental conditions produced during these tests enable a quantitative study of holding at the edge, residual water and drainage.

3.3.1 Holding at equilibrium

The means calculated in stabilized mode give respectively:

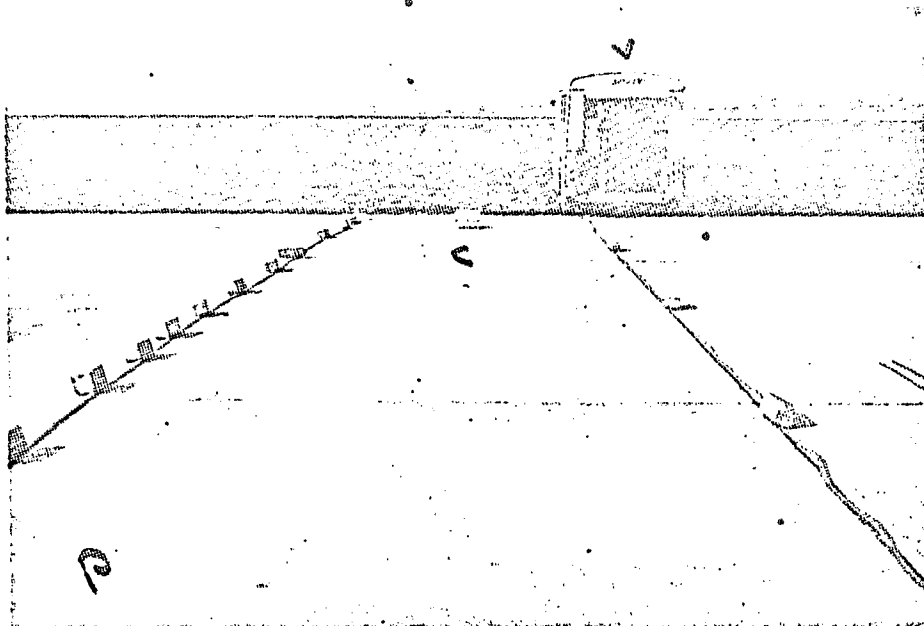
Point 1 (G) ⁹	1808 cps/10" or 10,848.cps/min	= 2.3 mm
Point 2 (G)	1550 " or 9,300 "	= 2.1 mm
Point 5 (NG)	1594 " or 9,564 "	= 2.1 mm

/33

9. Henceforth, G will designate tests relating to the grooved lot and NG those corresponding to the non-grooved lot.

The succession of the measurement is described in detail in annex II (points 1, 2 and 5).

Taking into account slight flaws in uniformity and the precision of the apparatus for measurement of water thickness, these values without being equal can be regarded as equivalent, i.e. that it can be assumed that they will not be a factor of differentiation from the viewpoint of the hydrodynamic condition.



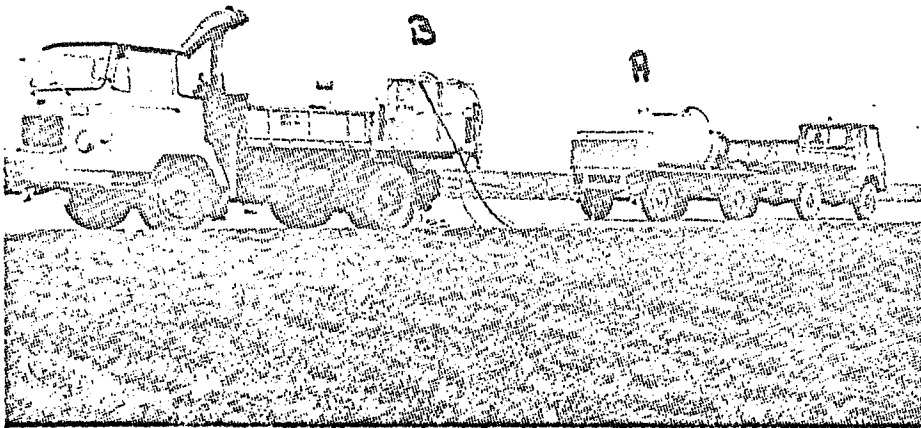
Demarcation
of one lot
(p); counter
(c) and mea-
surement veh-
icle (v)



Spraying
ramp on
grooved
concrete

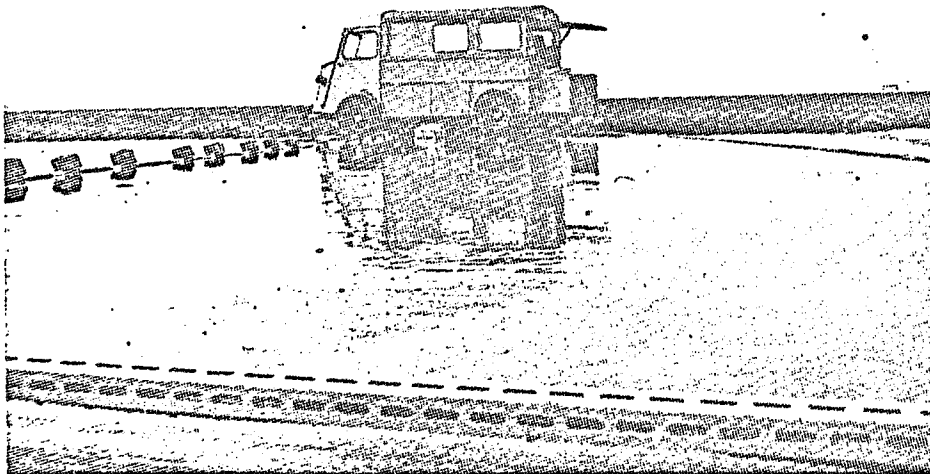
10

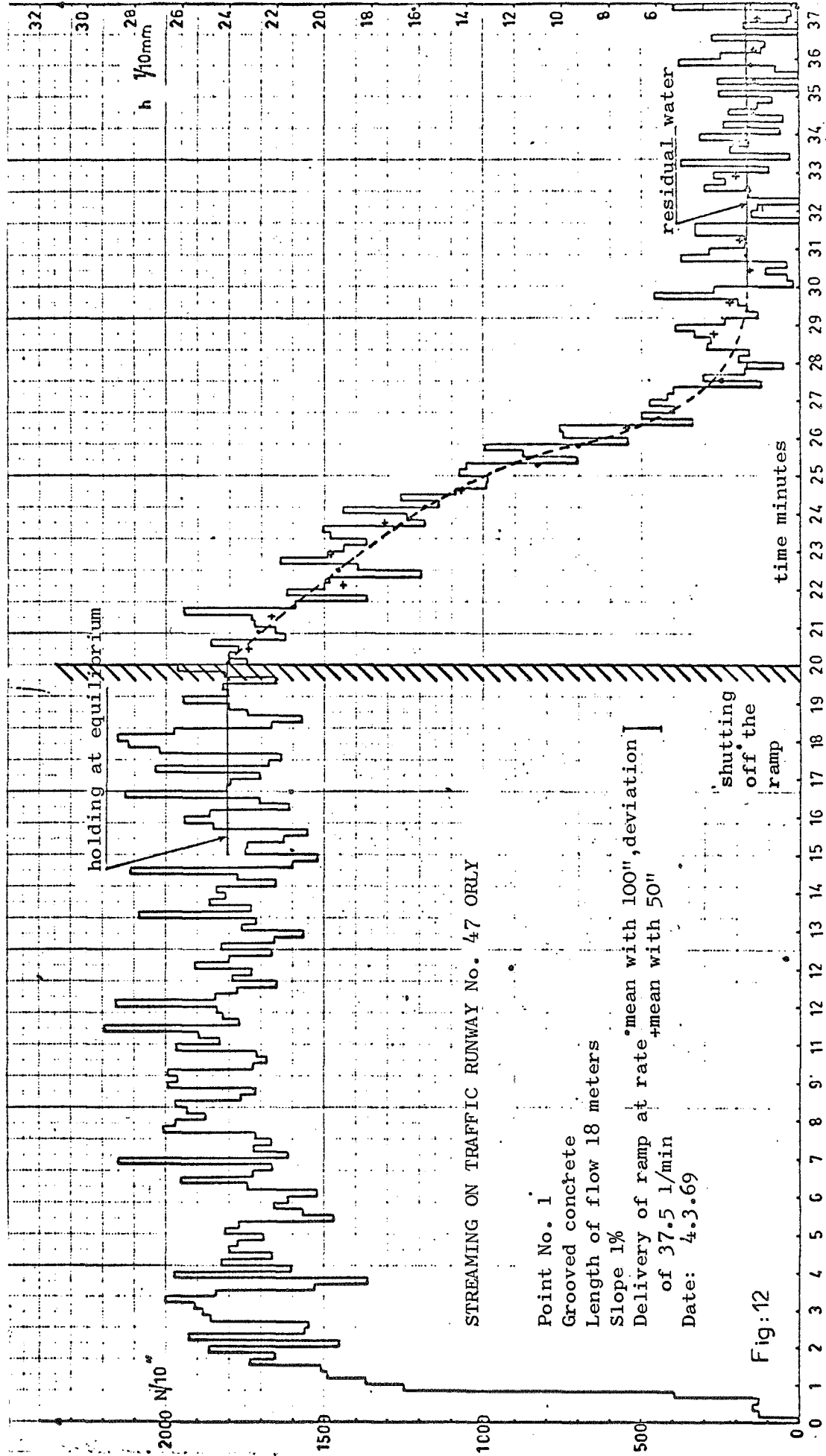
Supply by
tank (A) and
constant
level system
(B)



11

View of a
non-grooved
lot, in
drainage





STREAMING ON TRAFFIC RUNWAY No. 47 ORLY

Fig:12

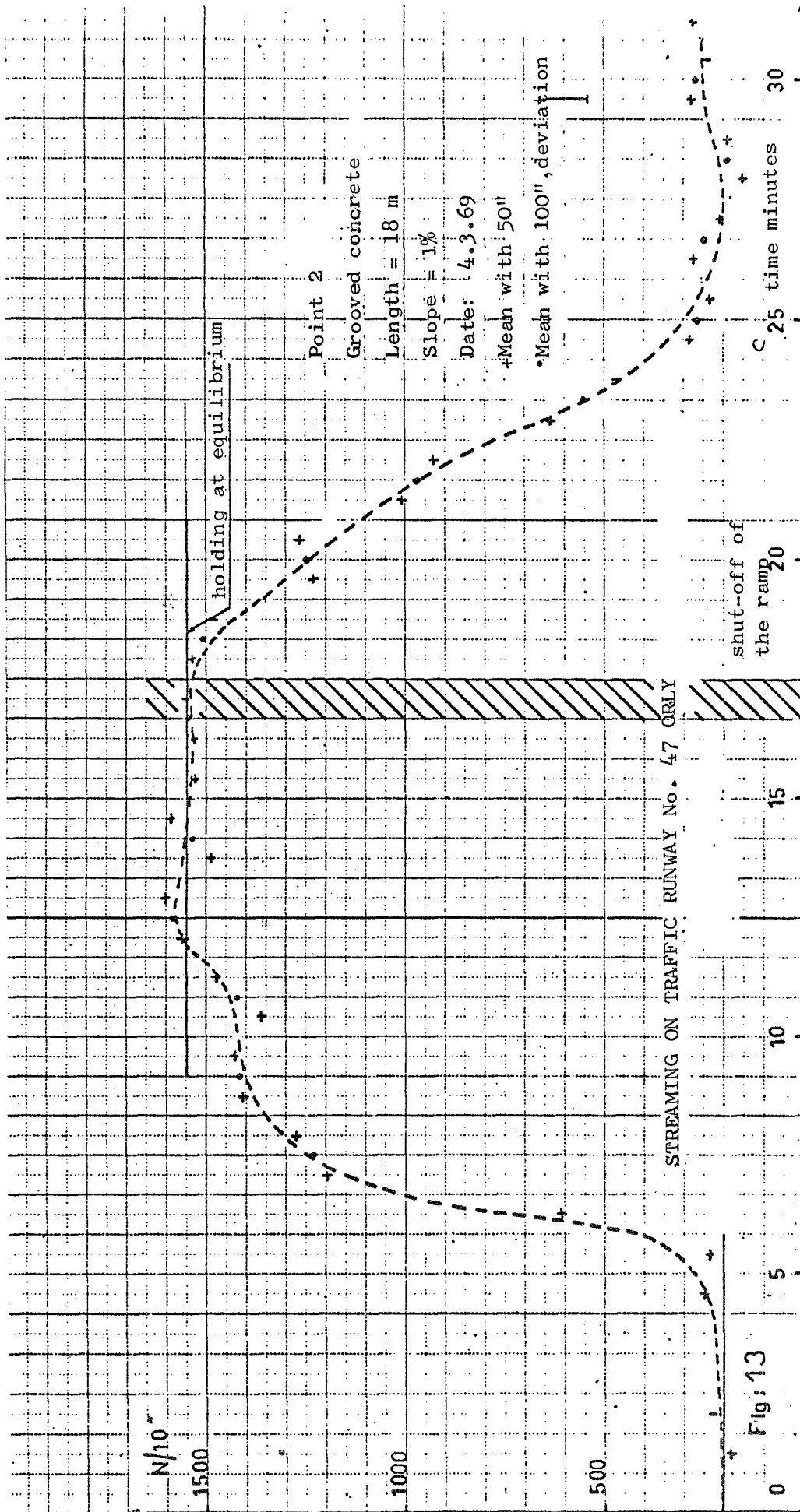
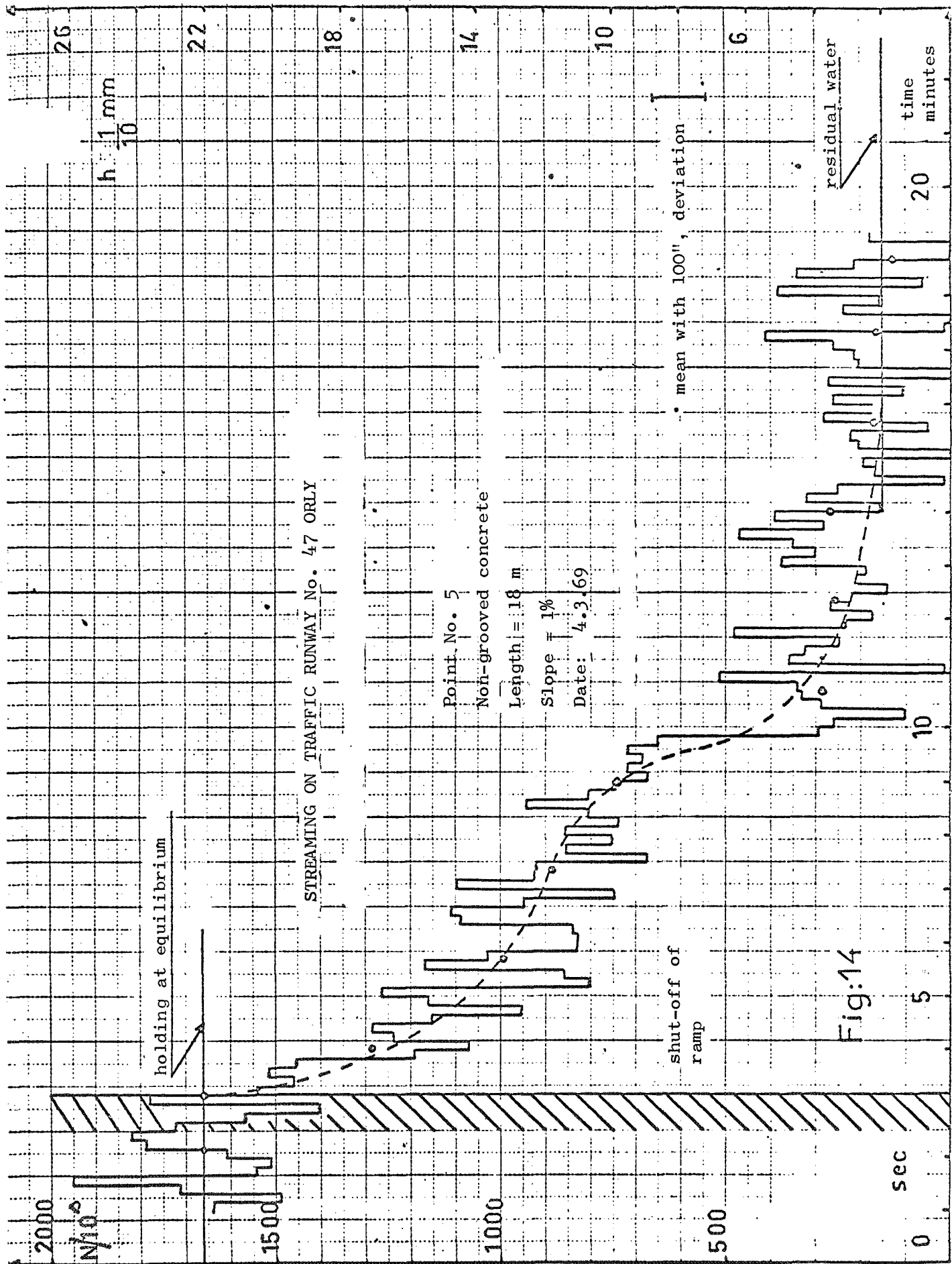


Fig. 13



The question comes up in the comparison of these thicknesses of water /33 film obtained at the edge through the intermediary of a ramp located overhead with values which could logically be expected in the presence of an addition of water distributed over the whole flow surface, such as an actual or artificial rain.

By disregarding the losses out of the lot, the flow q_e at the edge can be taken as equal to the flow of the ramp or approximately 40 l/min. This flow would be obtained by an intensity i of the rain distributed on surface S of the lot, i.e. it is true that:

$$q_e = i \cdot S$$

in the case of $S = 54 \text{ m}^2$, whence

$$i = 44 \text{ mm/hr}$$

corresponding to a very violent rain. By applying formula (1), attributed /34 to Izzard, it follows that:

$$k_{\text{edge}} = k l^{1/3} = 3.42 \text{ mm (in which } k = 0.0028 \text{ and } l = 54 \text{ feet)}$$

In this way, for the same flow at the edge, the thickness of a water film created by a rain would be approximately 3.4 mm whereas for a supply by ramp to the upper part of the slope, only 2 to 2.3mm are obtained. Izzard assumes that the mean thickness (i.e. a constant fictitious thickness along the flow) is equal to $3/4$ of the thickness at the edge or 2.5 mm which is on the same order of magnitude. In this way, then, with a supply by ramp, there is produced a film whose thickness is perceptibly constant the whole length of the slope with possibly a slight thinning towards the edge. The permanent hydrodynamic condition is therefore probably quite different from the one produced with a rain.

3.3.2 Residual water

The means (annex II) calculated in the terminal part of the drainage curves provide respectively:

Point 1 (G)	177 cps/10"	(1062 cps/min)	or 0.22 mm
Point 2 (G)	202 "	(1212 ")	or 0.27 mm
Point 5 (NG)	90 "	(540 ")	or 0.12 mm

It should be noted that at this level the precision of measurement is obviously quite low because of shortening of stabilizations with the residual water: it is in the vicinity of 0.13mm (annex III).

The residual waters therefore cannot be considered as significantly different.

3.3.3 Drainage

/35

The production, for holding at equilibrium, of levels which are perceptibly equivalent owing to the lateral channeling and constant supply allows undertaking the comparative study of drainage under quite good conditions of reproducibility.

We have seen that there is most likely a relation of type (4) between flow q , the mean height of the water film k and time t :

$$q = S \frac{d\bar{h}}{dt} = At^{-b} \quad (4)$$

whence by integration

$$\bar{h} = at^{-b} + c^a \quad (5)$$

Now, we have numerical values proportional to the thickness of water (in counts/10 s) which give the gradual development of the water film according to the various instants of the drainage at a very well located point, the edge. It is then possible to make the following hypothesis and test it, to the effect that function (5) is likewise valid for the local thickness k and not only t for the mean thickness, or:

$$k = at^{-b} + \text{const.} \quad \begin{array}{l} a, b \text{ numerical coefficients} \\ (b \text{ positive}) \end{array} \quad (6)$$

Let us note that it is possible to grasp the significance of the integration constant. Indeed, when the time increases indefinitely, it is known that the thickness of the film decreases and tends, by the very definition of residual water itself, towards the latter. Therefore, it follows

that:

$$h_t \rightarrow \infty \rightarrow \text{const.} = I$$

Ultimately, for the assumed functions of drainage, we have the expression:

$$k = at^{-b} + I \quad (7)$$

k = thickness of water film
I = residual water
t = time
a, b = coefficients (b is positive)

In order to test the validity of this hypothesis, the values of $k \cdot I$ (with counting unit number of counts per 10 seconds) and the time in seconds will be plotted as log-log coordinates. It should be possible to produce straight lines analogous to those of figure (3). The detailed calculations are provided in annex II and the curves are plotted on figure (15).

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Obviously, straight lines are not produced. On the other hand, several comments can be made.

1. Short of 350 s, approximately, the relative curves with grooved concrete (G) are quite alike in that they show a distinct curve which abruptly becomes very pronounced in the region of the point:

350 s
600 - 800 cps/10s or 0.9 mm

As far as the relative variation with the non-grooved (NG) concrete is concerned, it can be depicted by a straight line.

2. Beyond 350 s (region II) the three curves are squeezed into a very narrow spherical line and although the points of each curve are quite scattered, it is possible, as a first approximation and taking into account the narrowness of the general cluster as well as the lack of precision characteristic of this low level of water thickness, to assimilate each curve to a straight line.

3. Two regions I and II have therefore been discriminated in which the

recession of the film thickness is each time log-log linear in the case of the non-grooved concrete and linear only in region II in the case of the grooved concrete.

4. It is then extremely tempting to consider that the variation of $k - I$ is accomplished with an abrupt transition of hydrodynamic condition corresponding to an instant in which the water thickness $k - I = 0.9\text{mm}$.

5. The small number of experiments carried out (one for non-grooved concrete and two for the grooved) considerably weakens these conclusions and contaminates these curves with great inaccuracy.

h-I in counts/10"

137

Stabilization

NR

Region I

Region II

RECESSION OF WATER FILM ON SMOOTH AND GROOVED CONCRETE

- grooved concrete
- △ non-grooved concrete

Origin of t: stop supply

Flow: 38 l/minute

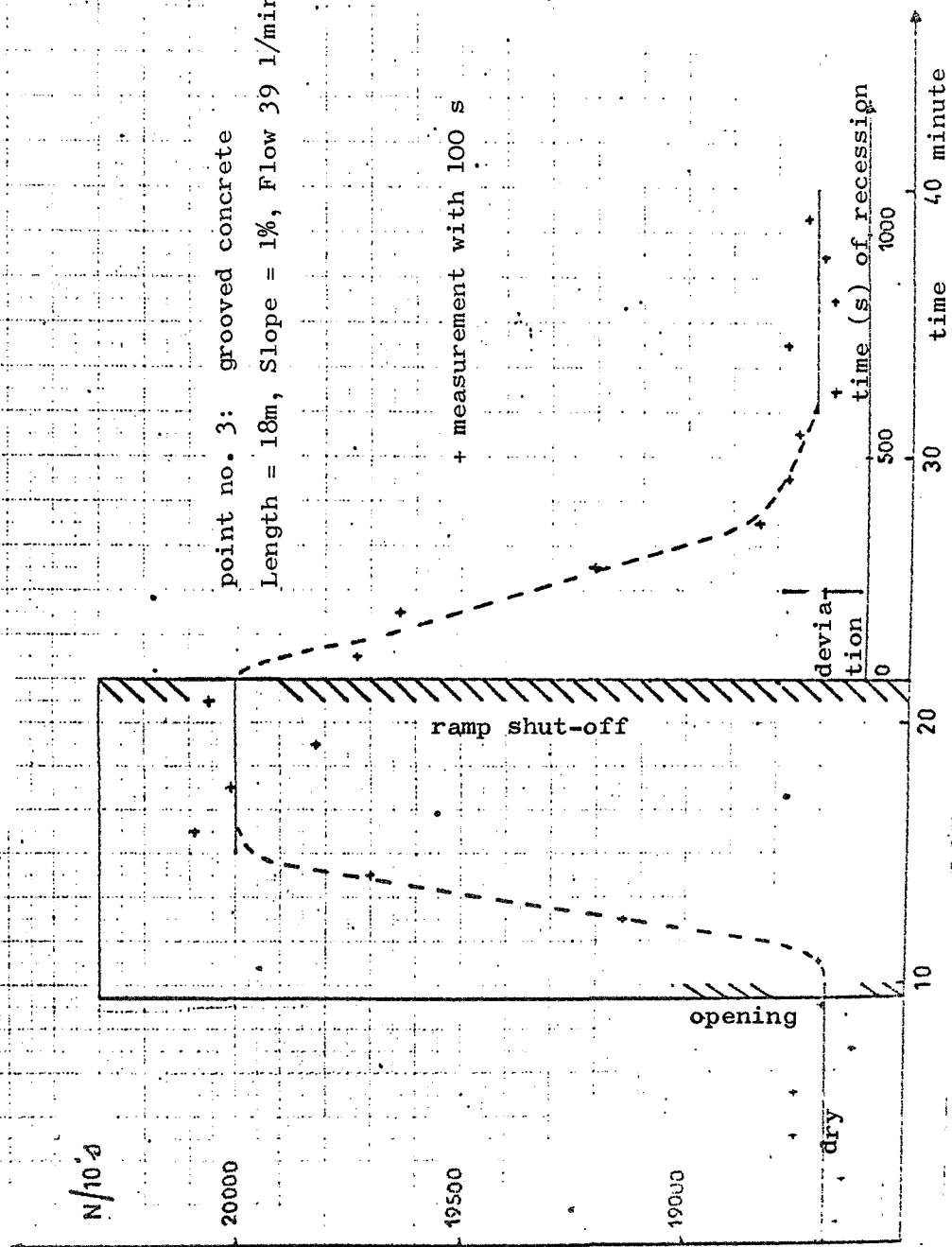
Length = 18 m

Slope = 1%

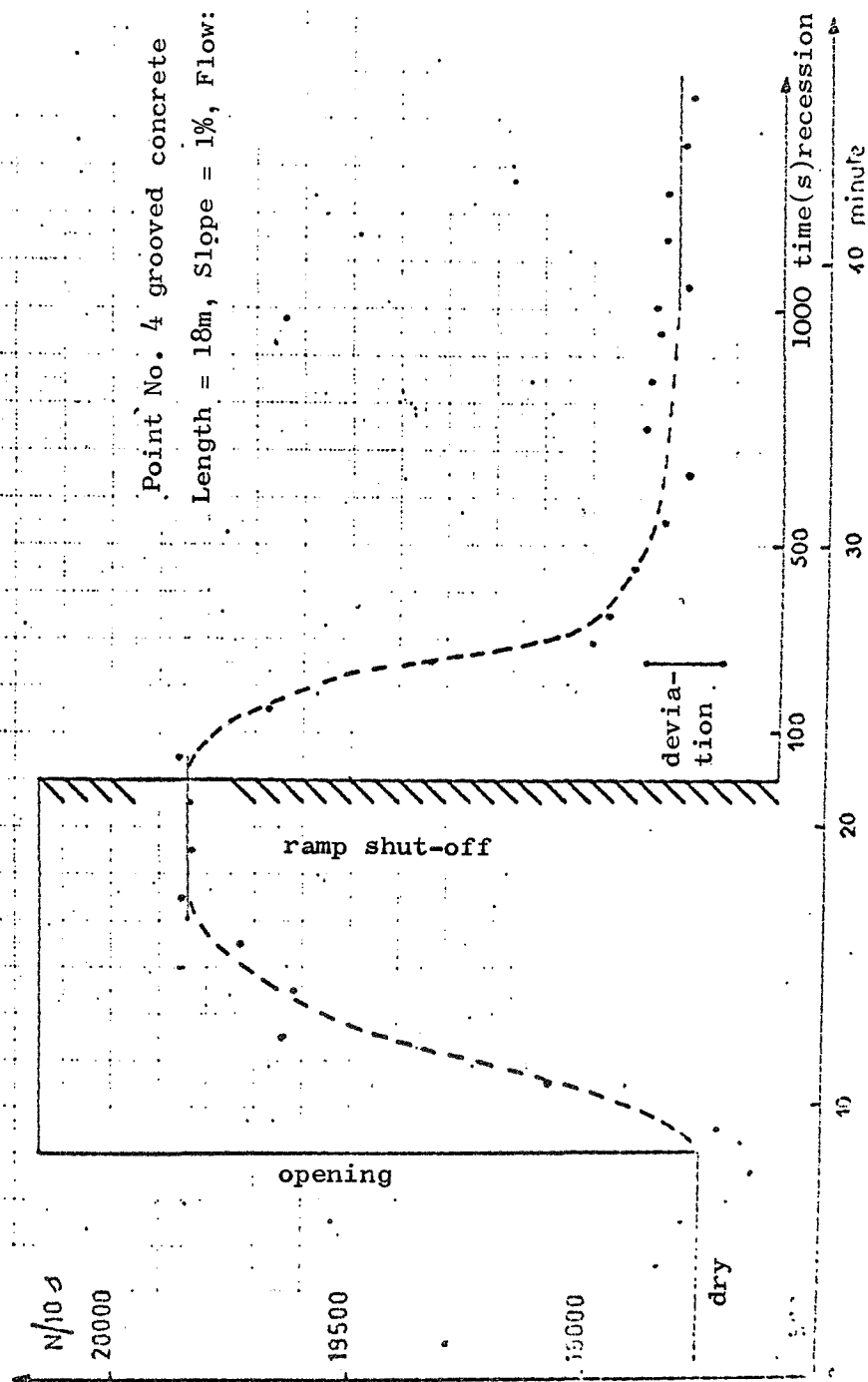
Fig. 15

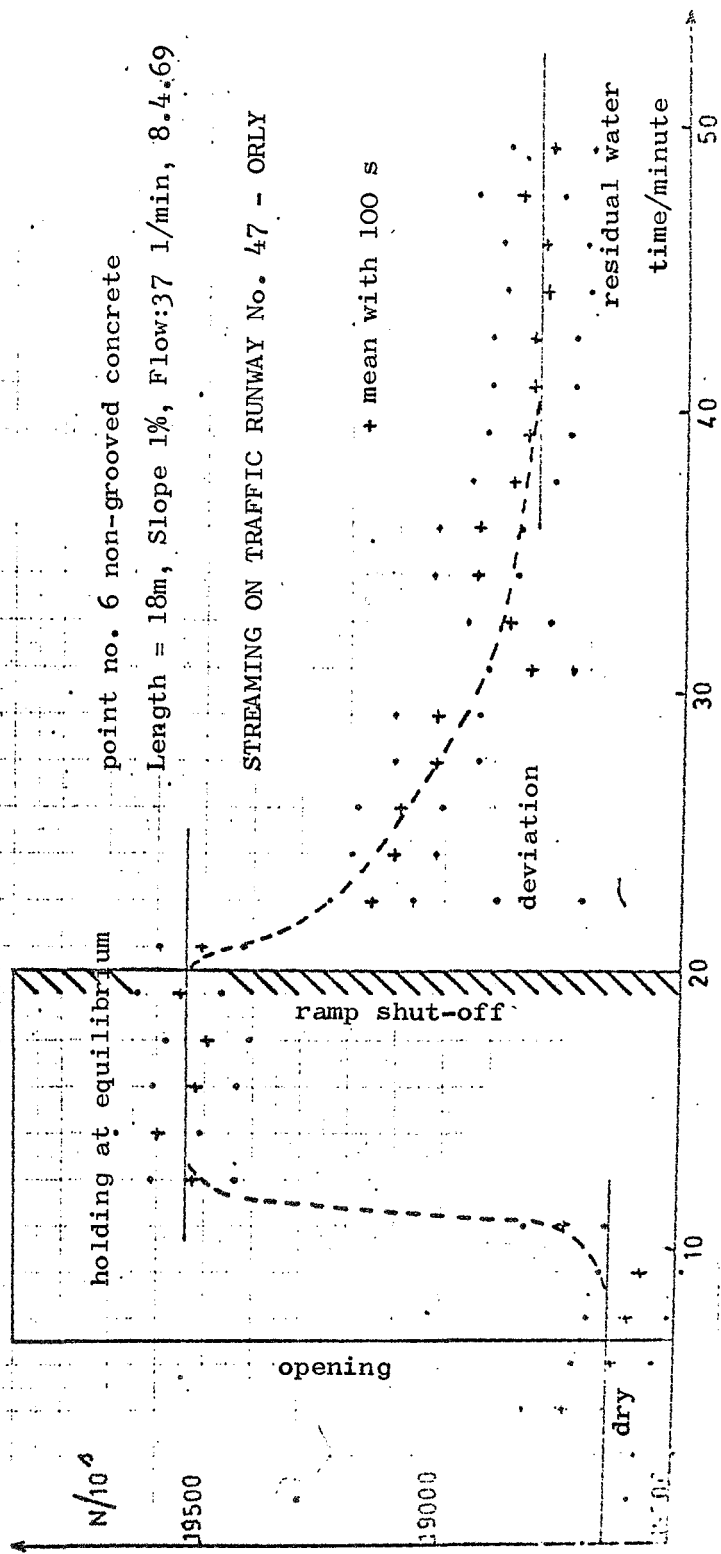
time (s)

STREAMING ON TRAFFIC RUNWAY No. 47 ONLY



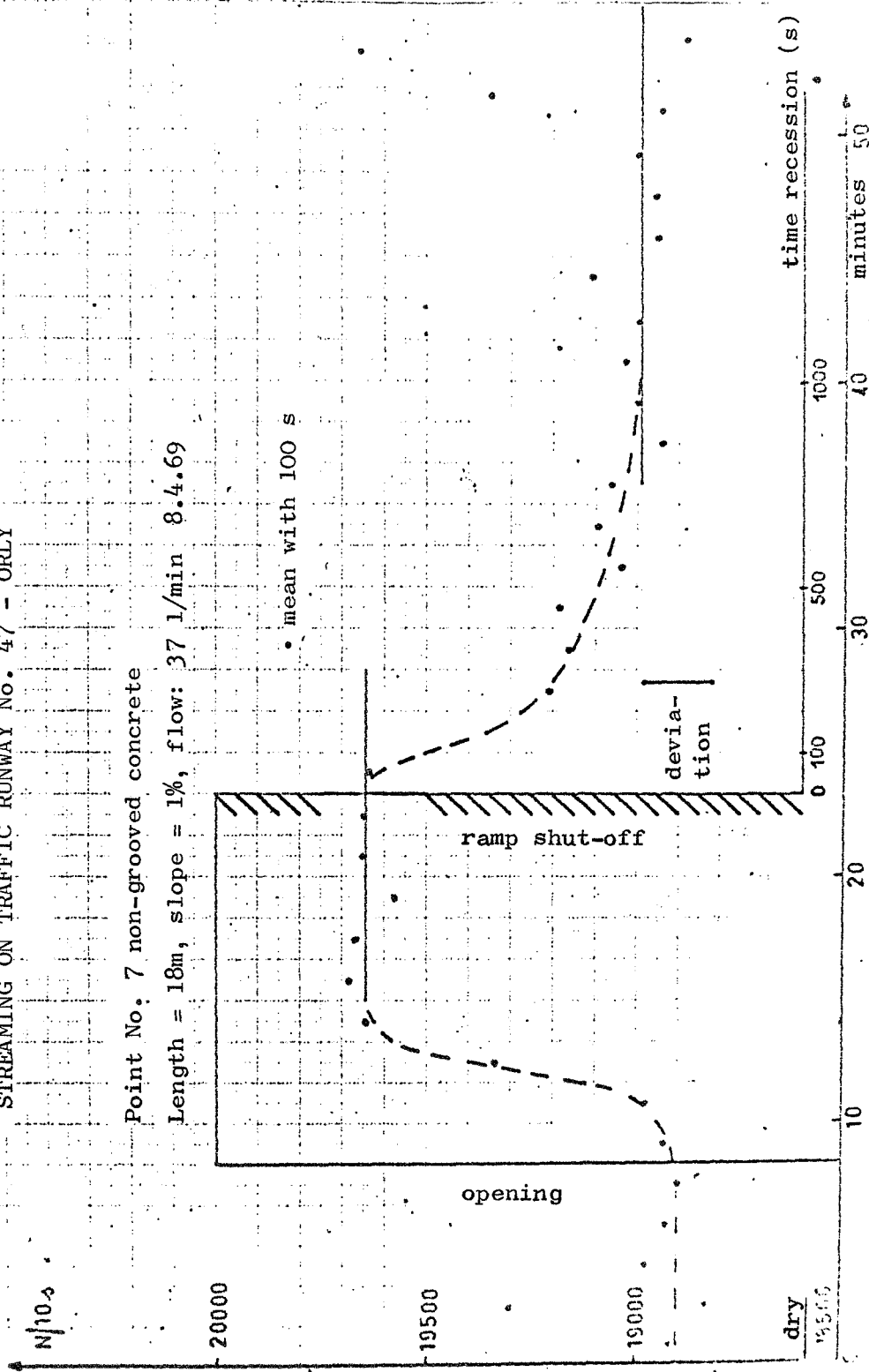
STREAMING ON TRAFFIC RUNWAY No. 47 ORLY



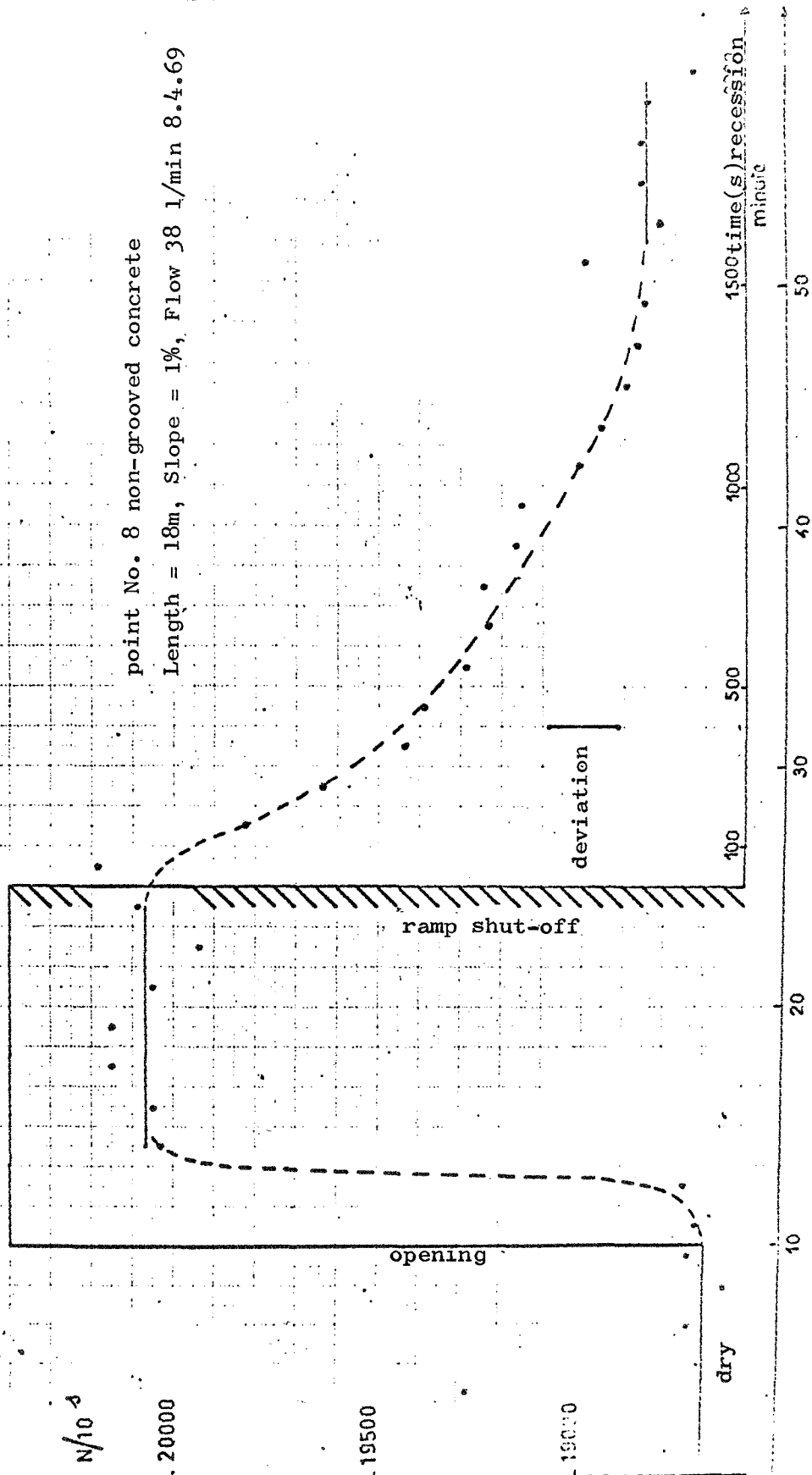


STREAMING ON TRAFFIC RUNWAY No. 47 - ORLY

Point No. 7 non-grooved concrete
 Length = 18m, slope = 1%, flow: 37 l/min 8.4.69



STREAMING ON TRAFFIC RUNWAY No. 47 - ORLY



At the same time, in order to confirm or amend the general direction of these conclusions and to specify the plot of the drainage curves or straight lines, a new series of experiments therefore became a requisite.

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3.4 Third test

Reusing the same experimental device as for the preceding test, i.e. ramp and constant supply delivery, demarcation of lots, it was possible to increase to eight the total number of experiments by performing two measurements on grooved concrete and three on non-grooved concrete in the same day. The values obtained are provided in annex II and the curves corresponding to each point are plotted on figures 16 to 20 using computational means set up for 100 s.

Several comments can be made:

3.4.1 The concentration curves are not comparable since the slight flaws in uniformity lead in the beginning to preferential flows and the arrival rate of the water under the counter at the edge is not the same depending on whether the surface is or is not moistened on a preliminary basis. The concentrations cannot therefore be studied.

3.4.2 The recession curves are quite different from each other even for a single type of surface. Nevertheless, a cursory survey reveals that drainage is always quicker in the case of the grooved concrete. The residual water condition is reached after approximately 10 minutes against 16, 20 and 25 minutes for the non-grooved surface.

3.4.3 The drainage curves show some wavy portions and especially towards the end of drainage. It is possible to arrange the latter in the domain of counting fluctuations or shall it be assumed that they reveal waves of the surge type?

3.4.4 Towards the middle of the drainage process, humps appear completely analogous to that of figure 14. This hump is always more distinct in the case of non-grooved cement.

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3.4.5 The residual waters are generally greater in the absence of grooving. They are compiled as follows (annex II):

Point 6 (NG)	166	counts/10"	(996 c/min)	or 0.22 mm
Point 7 (NG)	414	"	(2484 c/min)	or 0.55 mm
Point 8 (NG)	153	"	(918 c/min)	or 0.20 mm
Point 3 G	32	"	(192 c/min)	or 0.043 mm
Point 4 G	58	"	(348 c/min)	or 0.077 mm

These values determined for the residual waters are certainly more reliable than those produced in the preceding test. In reality, they have always been produced at least 30 minutes after drainages as against 20 minutes at the most at the time of the second test.

The conclusion relating to residual waters is therefore clear. The residual water after approximately 30 minutes of drainage is at the most on the order of 1/10 of mm with a grooved cement and greater than 2/10 for a conventional texture. The differences are significant for here the inaccuracy of a 1/10 of a mm of the calibration straight line does not become a factor since the same type of surface is involved (cf. paragraph 2). Indeed, water exclusively filling the grooves does not significantly affect the computation. The surface ratio is favorable. Furthermore, the accuracy of measurement is improved by a very long wait towards the end of drainage and an essential dry computation (annex III).

3.4.6 Holding at equilibrium

The computations $(N - N_o)_{stab.}$ are relative to the thicknesses of water in permanent condition (N_o is the dry computation; these values are provided in annex II). Translated into millimeters of water, they show the holdings at equilibrium:

Point 6 (NG)	894	cps/10"	(5364 cps/min)	or 1.19 mm
Point 7 (NG)	1068	"	(6408 ")	or 1.43 mm
Point 8 (NG)	1378	"	(8268 ")	or 1.84 mm
Point 3 G	1312	"	(7872 ")	or 1.75 mm
Point 4 G	1084	"	(6504 ")	or 1.45 mm

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The holdings are therefore rather only slightly scattered between 1.2 and 1.8 millimeters, since surface flaws greater than 0.6 millimeter should be rather frequent.

It is difficult to define the general drainage rate for each of the surface types by mere examination of curves 16 to 20. On the other hand, the situation is considerably clarified when, blocking the relative results at points 1 to 4 (G), on one hand, and 5 to 8 (NG), on the other hand, the means may be produced in both these groups for the various values $N - N_0$ in time (Annex II). Both curves corresponding to the drainage of the grooved concrete and the ungrooved concrete are shown in figure 21. Some features appear quite clearly.

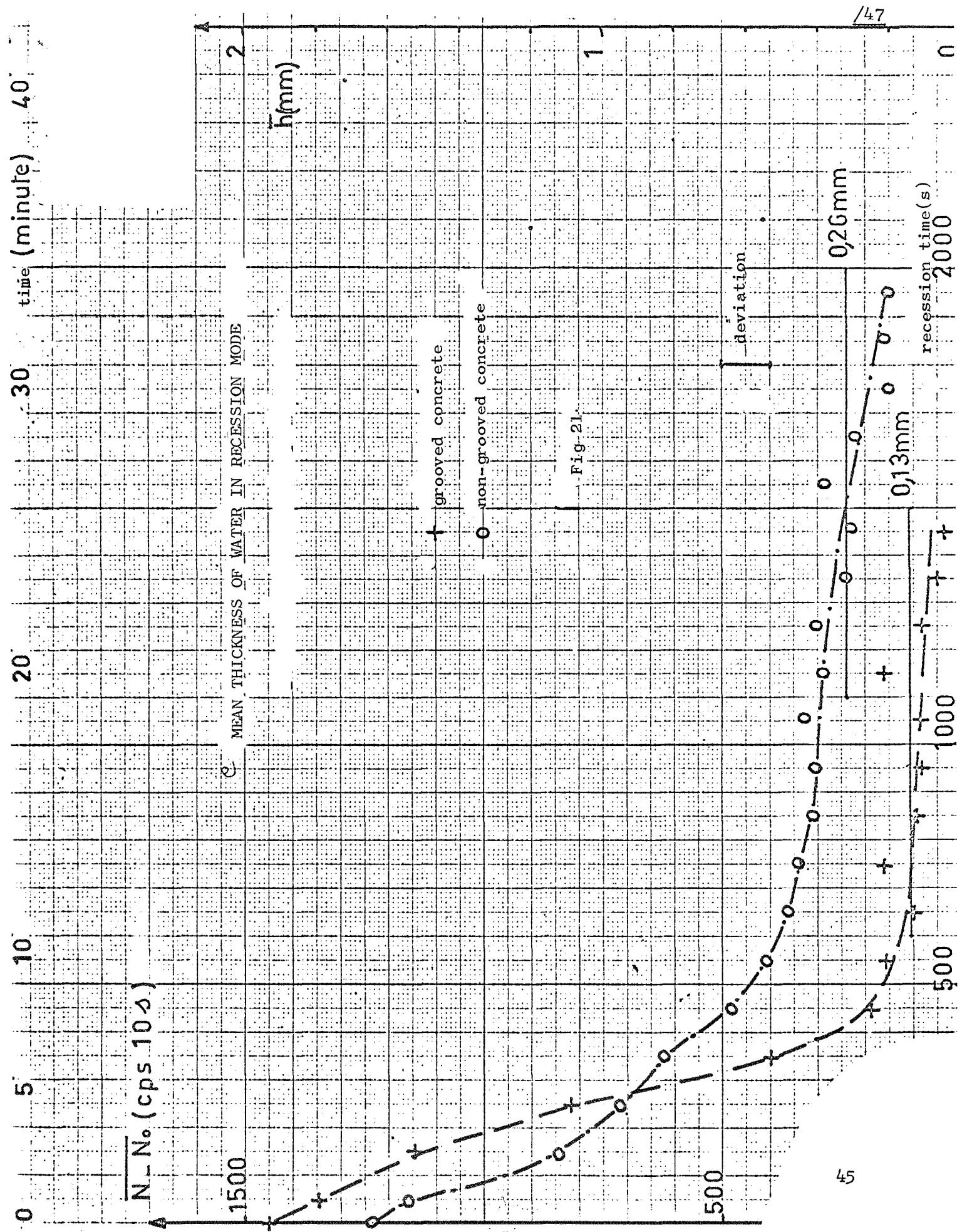
1. The recession of thickness of the water film at the edge is on the average much quicker and reaches a lower limit in the case of the grooved concrete.

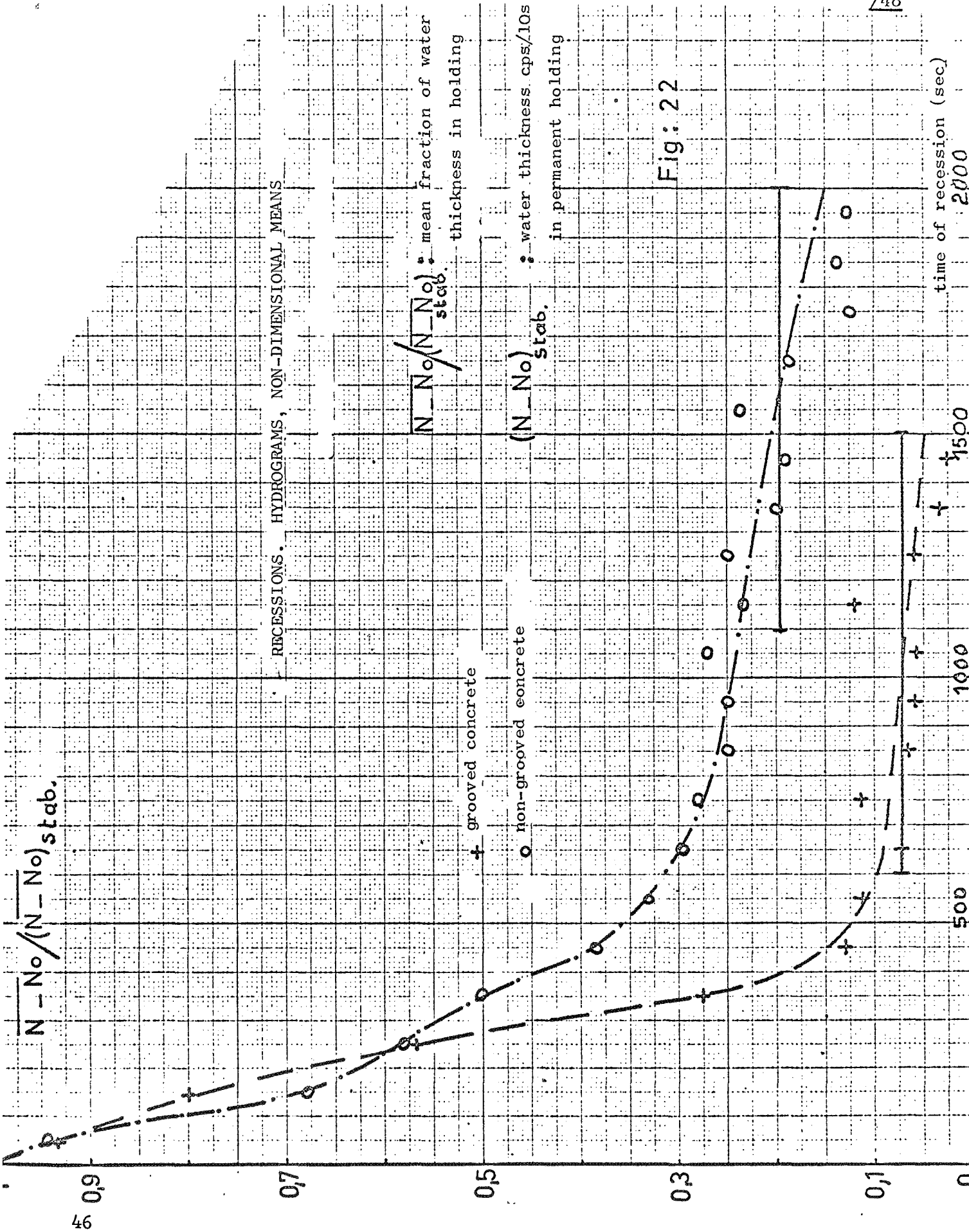
2. The curves are not completely smoothed by the establishment of the mean. There are changes in curves and wavy forms during and at the end of drainage.

3. The holdings at equilibrium, i.e. the water levels at beginning of drainage, are very slightly different. In order to compensate for this offset, it is possible to plot curves without dimensions by taking (fig. 22) as ordinates the values of

$$\frac{N - N_0}{(N - N_0)_{\text{stab.}}}$$

the differences are in this case better responsive. The validity of this normalization operation rests in the hypothesis that if the level of water on the non-grooved part was restored, by increasing delivery from the ramp, to the level prevalent on the grooved part (approximately 16% in difference), the hydrodynamic condition of the recession would not be changed. It can be taken into consideration and a justification will be found further on in the examination of log-log curves.





4. The measurement of a drainage rate can be quite difficult to carry /49
out since the slope of recession curves constantly vary. It is nevertheless possible to try to characterize each recession by a gross coefficient measuring the drainage time to 90%, for example. The operation is awkward on figure 22 and it is preferable to restore the final point of each drainage to a common value. This result is obtained by taking the fraction \bar{H}_r as a function of time:

$$\bar{H}_r = \frac{\overline{N - N_o - I}}{(N - N_o - I)_{stab.}}$$

which provides the plots of figure 23.

Let us recall that N designates the computation during recession, N_o the dry computation, I the computation suited for the residual water, $N - N_o - I$ their mean out of four experiments, $(N - N_o - I)_{stab.}$ this same quantity during the period of holding at equilibrium (annex IV). As hydraulic notations there would be:

$$H_r = \frac{D - I}{D_1 - I}$$

It is then possible to plot on figure 23 a straight line of ordinate 0.1 and characterize the drainage rate by a gross coefficient $T_{(d\ 90\%)}$ which marks off the duration of 90% of the drainage:

$$T_{(d\ 90\%)} = 400 \text{ seconds for the grooved concrete}$$

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$$T_{(d\ 90\%)} = 900 \text{ seconds for the non-grooved concrete}$$

RECESSION

NON-DIMENSIONAL MEAN HYDROGRAMS

Fraction of the thickness of the water film streamed

$$\bar{H}_r = \frac{N - N_{o-1}}{(N - N_{o-1})_{stab}}$$

as a function of time

+ grooved concrete
o non-grooved concrete

Fig: 23

drainage to 90 %

time (s)



5. This coefficient can appear too coarse or arbitrary and if it is desired to proceed further in the analysis of hydrodynamic conditions, it is possible to use the log-log recession of the thicknesses of water film already illustrated by figures 3 and 15.

If the $N - N_o - I$ values relating to each experiment are plotted on the same chart, the system is inextricable and confused. It is nevertheless simplified by merely taking the two means relating to the four experiments on grooved cement, on one hand, and to the four experiments on non-grooved cement, on the other hand. It is even more ingenious to take the non-dimensional mean streamed heights:

$$\bar{H}_r = \frac{N - N_o - I}{(N - N_o - I)_{stab.}} \quad (cf. fig. 24)$$

Curves similar to those of figure 15 are found but overlapping. They have been specified in their plot and confirmed by the "mean" operation.

Three regions are discriminated.

At the beginning of drainage, the behavior is the same: no perceptible effect of the grooving for 50 seconds.

Beginning from there, both conditions appear to be considerably differentiated, whereas, in the case of the grooved cement, the recession of the water thickness is kept at a relatively slow rate then is swiftly accelerated (with log-log coordinates); in the case of the non-grooved cement the rate is clearly linear (D_1).

RECESSION

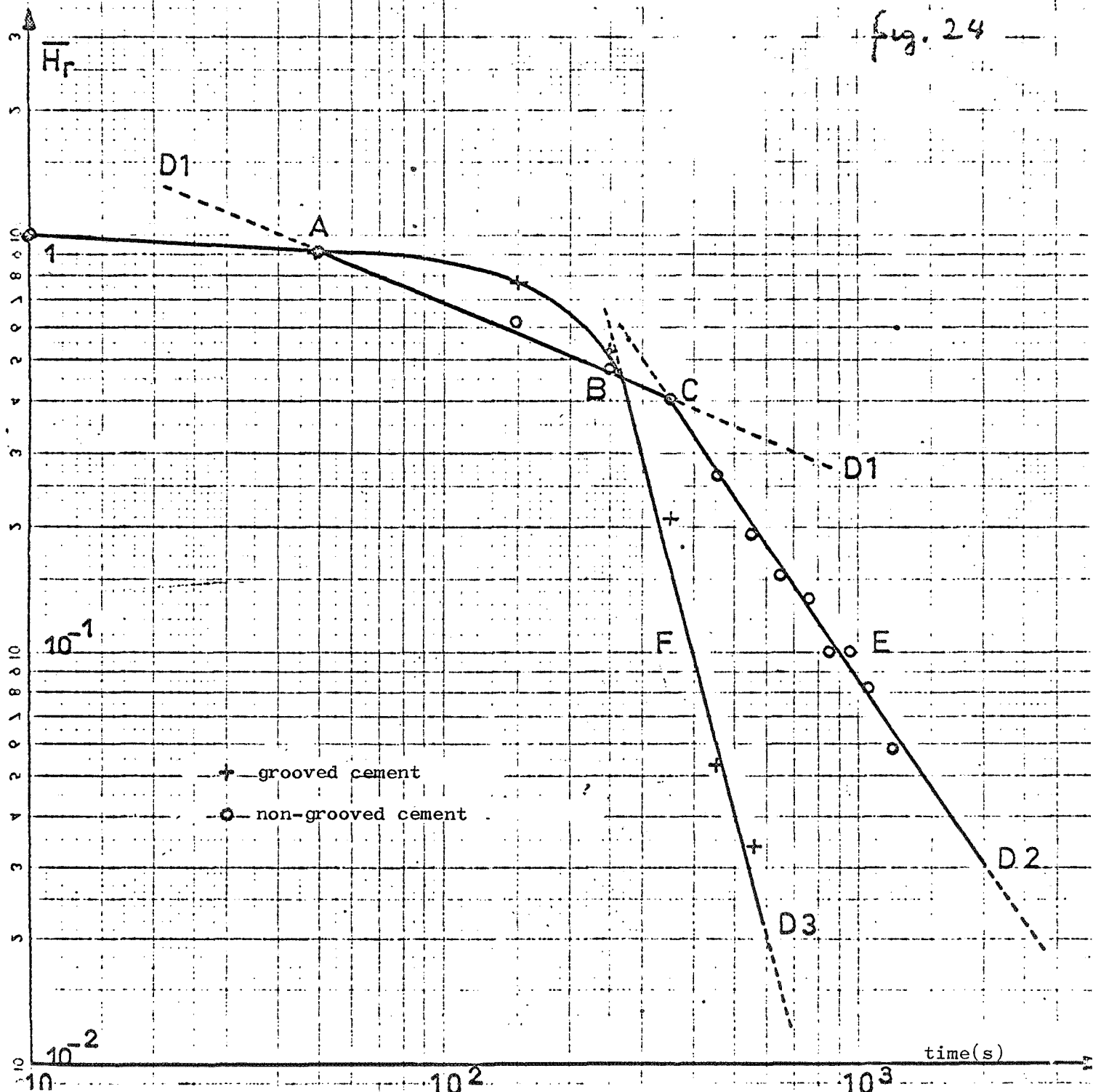
NON-DIMENSIONAL HYDROGRAM

Fraction of the thickness streamed

$$\bar{H}_r = (\bar{N}' - I) / (\bar{N}' - I)_{stab}$$

stab

Fig. 24



Then two other linear log-log conditions begin (D_2 and D_3), rather /53
more slowly and also, in the case of the non-grooved concrete (D_2), with
a gentler slope.

One possible interpretation of the behavior of fluid in these three
regions can be proposed.

In the first 50 seconds, we are probably in the presence of a quick
transitional phase which leads from the state of equilibrium with flow
supplied in the recession mode by a tipping of the fluid layer and which,
owing to the great thicknesses of water present, is independent of the
grooving.

Beyond these 50 first seconds, in the presence of grooves, the transi-
tion appears to continue for approximately 200 seconds whereas, in the
case of non-grooved cement, a stable and well characterized condition
appears to last approximately 300 seconds. Everything occurs as if the
grooving introduced at the beginning a turbulence which slowed down the
flow only to later on expedite it, all this probably upsetting the log-log
condition.

Beginning from heights of water estimated respectively at 0.9 mm (G)
and 0.5 mm (NG), the two flows use similar rules in linear log-log modes
with, nevertheless, differing inclinations. A domain is approached in
which the effect of the roughness of the surface should prescribe its
own rule, differing in its terms and conditions depending on the absence
or presence of the grooving which, by encouraging lateral drainage, increases
the rate of removal of the water film.

The linear log-log rule therefore appears quite specific for laminar
conditions and more particularly for those which are carried out with a
thin layer.

It is possible to provide a quantitative expression for these rules
for recessions of water film starting from the experimental data of figure
24. With a general rule:

$$\bar{H}_r = at^{-b}$$

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\bar{H}_r streamed thickness as
a non-dimensional unit
t in seconds

in the case of the various straight lines D_1 , D_2 and D_3 the a and b coefficients (Annex V) are the following:

	D_1 (NG)	D_2 (NG)	D_3 (G)
a	4.9_{02}	$3.0_{83} 10^3$	$5.2_{64} 10^8$
b	0.4_{19}	1.5_{19}	3.7_{36}
Rule of recession	$\bar{H}_r = 4.9t^{-0.42}$	$\bar{H}_r = 3.10^3 t^{-1.52}$	$\bar{H}_r = 5.3.10^8 t^{-3.74}$

In addition to the inherent advantage of being able to discriminate so clearly the successive hydrodynamic conditions, this demarcation into domains of uniform flow allows the more accurate computation of the mean rates of recession of the thickness of water film.

Mean rates of recession of the streamed fraction

(dimension t^{-1})

Region OA

$$NG : \frac{1-0.930}{50} = \frac{0.070}{50} = 1.4 \cdot 10^{-3} s^{-1}$$

$$G : \frac{1-0.924}{50} = \frac{0.076}{50} = 1.52 \cdot 10^{-3} s^{-1}$$

(AC) NG

(AB) G $\frac{1.25 \times 10^{-3}}{250 - 50} = \frac{1.25 \times 10^{-3}}{200} = 1.25 \times 10^{-5}$

Regions CD_2 /- B D_3

$$(CE) \text{ NG} \quad \frac{0,402 - 0,102}{950 - 350} = \frac{0,300}{600} = 0,5 \cdot 10^{-3} \text{ A-1}$$

$$(BF) \text{ G} = \frac{0.525 - 0.100}{400 - 250} \cdot \frac{0.426}{150} = 2.81 \cdot 10^{-3} \text{ A}^{-1}$$

It is possible to visualize these different mean rates on the same diagram (fig. 25)

Mean recession rates
of streambed thickness

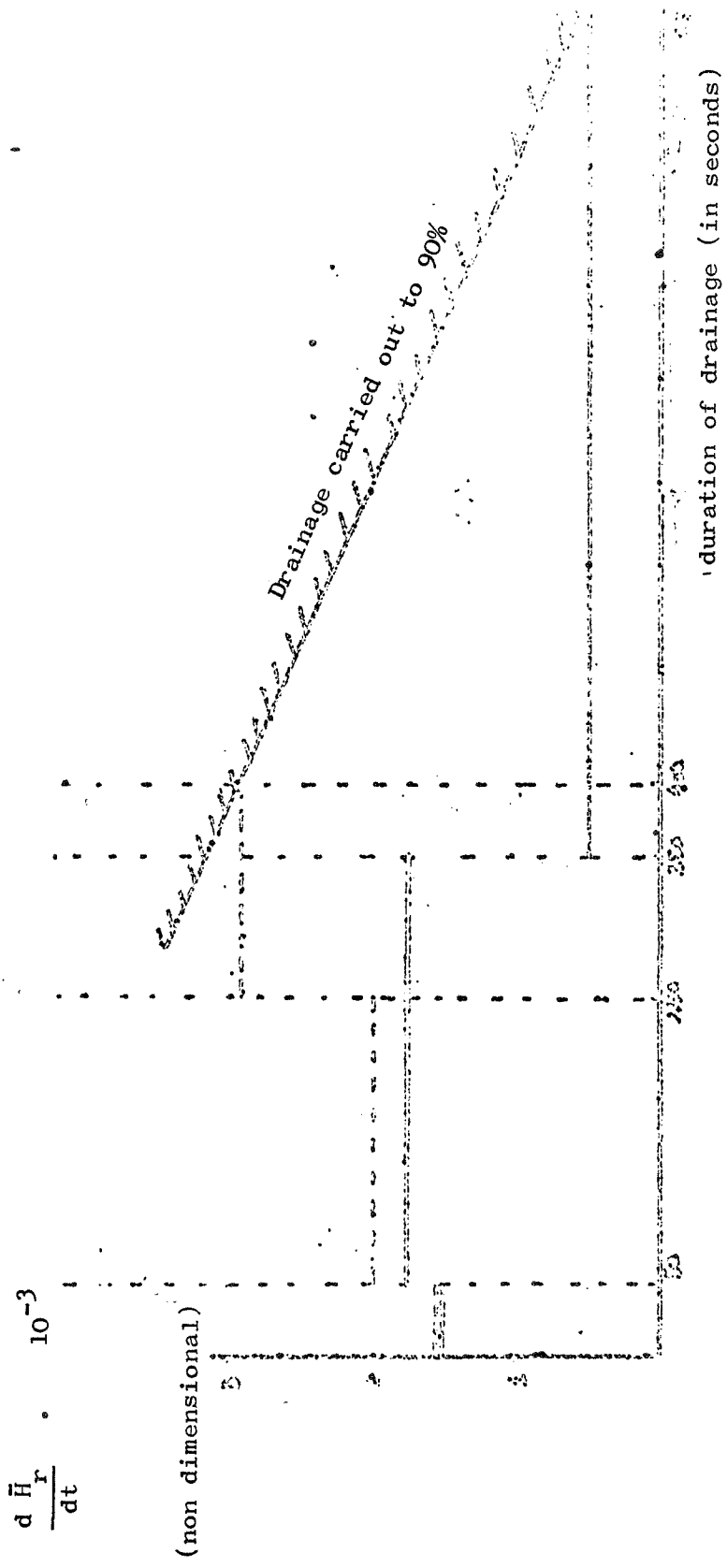


Fig. 25 Mean recession rates of streambed water thickness at various stages of drainage:

on grooved concrete -----

on non-grooved concrete —————

The application of the Central Laboratory of Civil Engineering (Laboratoire Central des Ponts et Chaussées) apparatus for measurement of water thicknesses with flows produced on an airport runway has amply demonstrated the qualities of accuracy and flexibility of use which were sought after in this equipment.

Through repetitive experimentation required as a consequence of the diversification of sites and climatic conditions, a very clear difference in behavior was revealed between drainage on grooved concrete and non-grooved concrete. The residual waters recorded go from 0.1 to 0.3 mm and to obtain the 90% drainage possible, the durations go from the single to the double (400 - 900 s).

The conclusions on the efficiency of grooving are therefore well established, and to such an extent that there could even be considered, if need be, a differentiation in the various types of grooving.

In addition, the apparatus allowed measurements of thicknesses of water film at all stages of streaming. At the same time, various successive hydrodynamic conditions of recession were clearly and authoritatively defined. This partial result could take its place within the scope of a more general study oriented on the geometrical roughness of highways.

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[Experimental Series on Artificial Highway Components], File
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Variation of recession flow as a function of time

(laboratory experiment, 7.10.68)

After having recorded the reduction in weight of an artificial surface, previously sprayed to the equilibrium point with a rain of given intensity, and which is progressively emptied, successive ordinates are picked off proportional to the instantaneous weight of the water retained by the surface. Their differences related to the unit of time determines the flow.

Experimental parameters

Artificial surface,	Code	: G ₁ 4
	area	: 600 cm ²
	edge	: 20 cm
	depth to sand:	2 mm
	slope	: 1 and 15%
Intensity of rain		: 365 mm/hr
Holdings at equilibrium		: 123 g (1%) and 50g (15%)
Flow at equilibrium		: 5.8 g/s

The following table is produced:

Time (s)	0	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175	185	195	205	215	225	235	245	255	265	275	285	295	305	315	325	335	345	355	365	375	385	395	405	415	425	435	445	455	465	475	485	495	505	515	525	535	545	555	565	575	585	595	605	615	625	635	645	655	665	675	685	695	705	715	725	735	745	755	765	775	785	795	805	815	825	835	845	855	865	875	885	895	905	915	925	935	945	955	965	975	985	995
AP/SE	0	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175	185	195	205	215	225	235	245	255	265	275	285	295	305	315	325	335	345	355	365	375	385	395	405	415	425	435	445	455	465	475	485	495	505	515	525	535	545	555	565	575	585	595	605	615	625	635	645	655	665	675	685	695	705	715	725	735	745	755	765	775	785	795	805	815	825	835	845	855	865	875	885	895	905	915	925	935	945	955	965	975	985	995
Slope 1%	0	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175	185	195	205	215	225	235	245	255	265	275	285	295	305	315	325	335	345	355	365	375	385	395	405	415	425	435	445	455	465	475	485	495	505	515	525	535	545	555	565	575	585	595	605	615	625	635	645	655	665	675	685	695	705	715	725	735	745	755	765	775	785	795	805	815	825	835	845	855	865	875	885	895	905	915	925	935	945	955	965	975	985	995
Slope 15%	0	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175	185	195	205	215	225	235	245	255	265	275	285	295	305	315	325	335	345	355	365	375	385	395	405	415	425	435	445	455	465	475	485	495	505	515	525	535	545	555	565	575	585	595	605	615	625	635	645	655	665	675	685	695	705	715	725	735	745	755	765	775	785	795	805	815	825	835	845	855	865	875	885	895	905	915	925	935	945	955	965	975	985	995

The straight lines plotted as log-log coordinates on figure 3 allow /60
giving as functions for recessions the following expressions:

$$\text{Slope 1\%} \quad \dot{q} = \frac{49.8}{t^{1.353}}$$

$$\text{Slope 15\%} \quad q = \frac{56.4}{t^{1.71}}$$

q, t: the mass flow (g/s) and the time (s).

NOTATIONS, MEASUREMENTS, MEANS

The title refers to the recapitulatory tables of measurements made for the grooved and non-grooved lots which also include the means for each type of surface. Subsequently, the measurement sheets for each one of the experiments is provided.

The thickness of water on the corresponding computation will be discussed without discrimination since the transition from either one is performed through the intermediary of the measurement apparatus constant (calibration straight line fig. 5).

Definition of the chief notations

The bars placed over a symbol designate the mean carried out over all the experiments taking place on the same surface type: grooved and non-grooved.

All computations are given in counts per 10 seconds.

N_0	Computation in dry state, mean established over several hundreds of seconds.
N	Computation carried out over 100 seconds in presence of a water film.
$N^1 = N - N_0$	Difference between wet and dry computations: proportional to the mean water height (fig. 5) or holding.
$N_0 + 1$	Computation in residual water state. The streaming is then practically halted. Mean made with several hundreds of seconds.
I	Computation characteristic of water film in residual water state.
$N^1 - I$	Computation characteristic of water streamed alone.

$$N_{stab.}^1 = (N - N_o)_{stab.}$$

Computation characteristic of water with holding at equilibrium. The mean is produced with several hundreds of seconds.

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$$(N^1 - I)_{stab.}$$

Computation characteristic of water streamed alone during the permanent condition (i.e. during holding at equilibrium).

GROOVED CONCRETE

RECAPITULATORY TABLE AND MEANS

POINT 1 (4.3)		POINT 2 (4.3)		POINT 3 (8.4)	
N _O	N _O : I	N _O : I	N _O : I	N _O : I	N _O : I
N _O : 18538	1:177	N _O : 18539	1:202	N _O : 18683	1:32
1606	1631	1550	1348	1312	1280
1709	1532	1504	1307	1041	1009
1462	1286	1246	1044	952	920
1191	1014	969	767	524	492
681	514	550	348	157	125
289	72	251	69	70	39
184	07	187	15	8	40
160	14	272	70	100	68
175	1			6	38
140	24			17	15
154	20			59	27
256	79				

GROOVED CONCRETE

RECAPITULATORY TABLE AND MEANS (cont.)

POINT 4 (3.4)		MEANS		Recession Time (s)	Phases of flow
N-N _o	N-I	N-N _o	N-I		
N _o : 12761	I: 58	N _o : 13641	I: 117	0	Permanent condition Holding at equilibrium
			I _{mean} : 107		
1024	1026	1438	1321	50	Shut-off of ramp
1097	1039	1339	1221		
912	834	1143	1026	150	Recession
568	510	813	693		
198	140	393	281	350	
85	27	161	46		
39	19	103	16	550	
130	72	165	49		
117	59	95	7	850	
102	44	66	1		
39	19	84	4	1050	
86	28	171	53		
47	9	47	9	1250	Residual water
35	22	35	23		

COMMENT: Two values for residual water have been given in the "means" column. One value I is the mean of the residual waters from the different measurement points. The other I value or I_{mean} is the residual water determined with N-N_o.

NON-GROOVED CONCRETE

RECAPITULATORY TABLE AND MEANS

POINT 5 (4.3)		POINT 6 (8.4)		POINT 7 (8.4)	
N'	N'-J	N'	N'-I	N'	N'-I
N _o : 18675	1:90	N _c : 18644	1:166	N _o : 18578	1:414
1594	1504	894	738	1068	654
1222	1132	866	701	1062	648
924	834	512	344	784	370
824	734	466	299	636	222
685	595	433	287	593	179
221	131	374	213	610	196
191	101	376	210	464	50
227	117	183	17	520	106
107	17	236	60	487	73
100	10	292	129	64	-50
63	-27	289	153	427	13
		218	32	422	39
		193	27	415	1
		181	15	525	121
		179	13	374	-40
		149	-17	380	-34
		157	-9	419	5
		205	39	364	-50
		142	-24		

NON-GROOVED CONCRETE

RECAPITULATORY TABLE AND MEANS (con.)

POINT ϕ (8.4)	MEANS		Recession Time (s)	Phases of flow
	N'-1	N'		
N ₀ :18688	1:153	N ₀ :18645	I:205 I means I:239	
1378	1225	1233	1027	Permanent condition Shut-off of ramp
1498	1345	1162	956	Recession
1138	985	839	633	
946	792	717	512	
745	592	619	413	
707	554	479	273	
599	446	407	201	
547	394	364	158	
556	403	344	138	
478	325	309	103	
468	315	311	106	
323	120	227	86	Residual water
265	112	293	46	
207	84	307	73	
183	30	245	1	
164	11	231	-13	
300	147	292	47	
125	-28	231	-13	
166	13	154	5	
168	15	168	15	
155	2	155	2	

Ramp delivery: 37.5 l/min

Computation in dry state: $N_o = 18584$ cps/10s (out of 100 s)

Subtraction :

Correction :

 $I = 177$

Dry Start :

Means/50s (cps/10s)	Means/100s (cps/10s)	Various means (cps/10s)	$N' - I$ (cps/10s)	Time (s)	Phases of flow
1793 1894 1922 1746 1812		$N'_{stab.} = 1808$	$(N' - I) = 1631$		Holding at equilibrium: De
				0	Shut-off of ramp
1742	1709		1532	50	
1670					
1440	1462		1286	150	
1484		$I = 177$			
1302	1191		1014	250	
1080					
834	691		514	350	
548					
345	259		82	450	Recession
173					
275	249		72	550	
223					
170	184		7	650	
196		$I = 177$			
119	160		-17	750	
200					
199	175		-2	850	Residual water
150					
137	140		-37	950	
143					
129	154		-23	1050	
179		$I = 177$			
274	256		79	1150	
238					

Ramp delivery: 39 l/min

Computation in dry state: $N_o = 18539$ cps/10 a

Subtraction :

Correction : 0 I = 202

Dry Start :

Means/50s (cps/10s)	Means/100s (cps/10s)	Various means (cps/10s)	$N' - I$ (cps/10s)	Time (s)	Phases of flow
181		I = 202			Preceding residual water
226	217				
208					
196	223				
251					
236	426	$N'_{stab.} = 1550$	1348		Concentration
616					
1197	1235				
1274					
1409	1418				
1428					
1364	1419				
1475					
1562	1582				
1603					
1488	1537	$N'_{stab.} = 1550$	1307	0 50 150 250 350 450 550 650 750	Holding at equilibrium
1587					
1532	1532				
1532					
1549	1541				
1534					
1484	1509				
1226					
1267	1246				
1010					
929	969		767		Shut-off of ramp
635					
465	550				
287					
234	260				
279					
223	251				
168					
207	187				
284	272				
					Recession

POINT No. 3, grooved

Date: 8/4/1969

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Ramp delivery: 39 l/min

Computation in dry state: $N_o = 18683$ cps/10s (with 500s)

(18652
18638
18750
18621
18687)

$N_o + I : 18715$
 $I : 32$

Dry start

Means/50s	Means/100s (cps/10s)	Various means (cps/10s)	$N' - I$ (cps/10s)	Time (s)	Phases of flow
	18686 19140 19700 20086 20015 19818 20001	$N_{stab.} = 19995$	1280	0	Concentration Holding at equilibrium Shut-off of ramp
	19724 19635 19207 18840 18774 18753 18675 18783 18677 18700 18742 (60s)				
		$N_o + I = 18715$	1009	50	Recession
			920	150	
			499	250	
			125	350	
			59	450	
		$N_o + I = 18715$	38	550	Residual water
			-40	650	
			68	750	
			-38	850	
			-15	950	
			27	1050	

POINT no. 4, grooved

Date: 8/4/1969

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Ramp delivery: 38 l/min

Computation in dry state: $N_o = 18761$ cps/10s (with 500s)

(18761
18760
18843
18794
18647)

$N_o + I = 18814$ cps/10s

$I = 58$ cps/10s

Dry start

Means/50s	Means/100s (cps/10s)	Various means (cps 10s)	$N' - I$ (cps 10s)	Time (s)	Phases of flow
	18720 19080 642 619 733 851 829 844	$N_{stab} = 19845$	1026		Concentration Holding at equilibrium Shut-off of ramp
	19858			0	
	673			50	
	329			150	
	18959			250	
	910			350	
	846			450	
	800			550	
	891	$N_o + I = 18819$	-19	050(sic)	Recession Residual water
	878			750	
	863			850	
	800			950	
	847			1050	
	845			1150	
	808			1250	
	796			1350	
			-23	1450	

POINT no. 5, non-grooved

Date: 4/3/1969

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Ramp delivery: 40 l/min

Computation in dry state: $N_o = 18673 \text{ cps/10s}$ $I = 90 \text{ cps/10s}$
(with 100 s)

Subtraction: 18609

Correction (made in the table) : -64

Dry start

Means/50s (cps/10s)	Means 100s (cps/10s)	Various means (cps/10s)	$N' - I$ (cps/10s)	Time (s)	Phase of flow
	1594 with 130s)	$N'_{stab} = 1594$	1504	0	Holding at equilibrium
	1222		1132	50	Shut-off of ramp
	924		834	150	
	824		734	250	
	685		595	350	
	221		131	450	
	191		101	550	
	207		117	650	Recession
	107		17	750	
	100	$T=90$	10	850	
	63		-27	950	
					Residual water

POINT no. 6, non-grooved

Date: 8/4/69

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Ramp delivery: 38 l/min

Computation in dry state: $N_o = 18644$ cps/10s (with 500s)

Dry start

$N_o + I = 18810$ cps/10s

$I = 166$ cps/10s

Means/50s (cps/10s)	Means/100s (cps/10s)	Various means (cps/10s)	$N' - I$ (cps/10s)	Time (s)	Phases of flow
	18605				Concentration Holding at equilibrium
	573				
	739				
	19525	$N_{stab} = 19538$	$N'_{stab} = 728$		
	597				
	521				
	496				
	552				
				0	Shut-off of ramp
19541/480	511		701	50	
19391/18917	154		344	150	Recession
19154/064	109		299	250	
121/074	097		287	350	
18988/19058	023		213	450	
19038/003	020		210	550	
18815/838	18827		17	650	
819/921	870		60	750	
948/930	939		129	850	
961/904	933		123	950	
940/18785	862		52	1050	
18799/876	837		27	1150	Residual water
880/770	827		15	1250	
774/873	823		13	1350	
786/800	793		-17	1450	
854/749	801	$N_o + I = 18810$	-9	1550	
849/844	849		39	1650	
773/799	786		-24	1750	

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$$I = 414 \text{ cps}/10\text{s}$$

Means/50s (cps/10s)	Measn/100s (cps/10s)	Various means (cps/10s)	N' - I (cps 10s)	time (s)	Phases of flow
	18922	18912	$(N' - 1)_{stab} = 654$		Preceding re- sidual water Ramp opening
	831				
	976				
	933				
	902				
	934				
	982	$N_{stab} = 19646$			Concentration
	19341				
	648				
	690				
	670				
	575				
	650				
	648				
			0	Shut-off of ramp	
19710/570	640		648	50	
439/285	362		370	150	
266/163	214		222	250	
189/154	171		179	350	
232/143	188		196	450	
028/056	042		50	550	
151/046	098		106	650	
050/080	065		73	750	
18875/19010	18942		-50	850	
18981/19029	19005		13	950	
19057/003	030		38	1050	
19018/18969	18993		1	1150	
19013/213	19113	$N_o + I = 18992$	121	1250	
18851/19054	18952		-40	1350	
19007/18909	958		-34	1450	
18989/19006	997		5	1550	
18975/910	942		-50	1650	

POINT. no. 8, non-grooved

Date: 8/4/1969

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Ramp delivery: 39 l/min

Computation in dry state: $N_o = 18688$ cps/10s (with 560s)

(18698/637/697/726/644/731)

$N_o + I = 18841$ cps/10s

Dry start

$I = 153$ cps/10s

Means/50s (cps/10s)	Means/100s (cps/10s)	Various means (cps/10s)	$N' - I$ (cps/10s)	Time (s)	Phases of flow
	18707				Opening of ramp Concentration
	739				
	20029				
	049	$N_{stab} = 20077$	$(N' - I)_{stab} = 1225$		Holding at equilibrium
	149				
	149				
	054				
	19943				
	20090			0	Shut-off of ramp
20124/247	20186		1345	50	Recession
19967/685	19826		985	150	
696/571	634		793	250	
425/441	433		592	350	
395/395	395		554	450	
229/345	287		446	550	
299/172	235		394	650	
252/236	244		403	750	
214/119	166		325	850	
176/136	156		315	950	
035/18987	011		170	1050	
19003/18904	18953		112	1150	
18871/920	895		84	1250	
812/930	871		30	1350	
863/842	852		11	1450	
19009/18968	988		147	1550	Residual water
18808/818	813	$N_o + I = 18841$	-28	1650	
813/896	854		13	1750	
872/840	856		15	1850	
838/848	743		2	1950	
	726 (60s)				

Relative accuracies with various computationsDeviations corresponding to the points and straight lines of the various diagrams

It will be assumed that a series of computations corresponding to states of equilibrium such as holding at equilibrium or the residual water condition, follows a Poisson's law.

Under these conditions it is known that the variance σ^2 is equal to mean m

$$\sigma^2 = m$$

We shall consider the computations produced in 10 s as the population elements.

Several means are used:

- computational mean (in a uniform population with 100 s, the variance will in this case be equal to:

$$\sigma^2 = \frac{m}{10}$$

- computational means (in a uniform population with 100 s in four experiments which we shall assimilate with repetition of the same. The variance will be given by:

$$\sigma_{\frac{1}{4}}^2 = \frac{m_{\frac{1}{4}}}{40}$$

- computational means with n points (each one representing 100 s) describing a state of equilibrium. Whence the variance:

$$\sigma_n^2 = \frac{m_n}{10n}$$

- the errors owing to the computations with measurement of water thicknesses will be systematically calculated by \pm two standard deviations.

1. Representative point with a mean produced in 100 seconds.

These points were used in the plotting of different concentration-recession curves (figs. 12 to 14 and 16 to 20).

Let us perform the calculation for the highest and lowest computations:

- Highest computation, holding at equilibrium of experiment
no. 1: 20392 cps/10s.
- Lowest computation (wet), residual water
no. 3: 18715
- Lowest computation (dry), residual water
no. 1: 18539

The corresponding variances are equal to:

$$\frac{20,392}{10} = 2039 \quad \text{or a standard deviation of} \quad \sigma = 45$$

$$\frac{18,715}{10} = 1872 \quad " \quad \sigma = 43$$

$$\frac{18,539}{10} = 1854 \quad " \quad \sigma = 43$$

Values which hardly differ from each other, $\sigma = 44$ cps/10 s will therefore be taken as the common value.

By calling (Δh) , the error made in the estimate of the height of water, strictly from the computational viewpoint, and with one point representing a mean with 100 s, it follows that:

$$(\Delta h)_{1=2\sigma} = \frac{88 \times 6}{450 \text{ s}} = 0.12 \text{ mm}$$

2. Representative point of a mean of four experiments

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An intermediate level is taken on figure 21, for example the point for which \bar{N}' : 700 cps/10s. It is true that:

$$\sigma^2 = \frac{19,345}{40} = 485 \quad \text{whence} \quad \sigma = 22$$

$$\text{and} \quad (\Delta h)_4 = \frac{44 \times 6}{4500} = 0.06 \text{ mm}$$

The accuracy, solely owing to computation, of the points of fig. 21

is calculated to

$$\pm 0.06 \text{ mm}$$

or $\pm 44 \text{ cps}/10 \text{ s}$

3. Straight line which is representative of a mean

3.1 Holding at equilibrium and residual water in each one of the experiments.

The holding as a permanent condition by producing the mean from a computation with 100 s from which N_o is subtracted. The advantage of calculating accuracy with this height of water is rather limited and we shall do without it. On the other hand, the residual water requires this calculation. The computation I characteristic of the water film in the residual water state is obtained by the difference

$$(N_o + I) - N_o$$

i.e. that the variance is given by

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$$\sigma_I^2 = \sigma^{2'} + \sigma^{2''} \quad \begin{array}{l} (\sigma' \text{ deviation with } N_o \text{ and} \\ \sigma'' \text{ deviation with } N_o + I) \end{array}$$

The following table provides details of the calculations and provides the computational accuracy for the relative residual waters at different measurement points.

3.2 Holding at equilibrium and residual water in curves depicting the means of four experiments.

- With mean holding the highest computation is relative to grooved concrete and was carried out with 132 times 10 seconds.

$$\bar{N}' = 20,079$$

- With mean residual water (the lowest wet computations)

$$\text{concrete G : } \overline{N_o + I} = 18750$$

$$\text{concrete NG: } \overline{N_o + I} = 18850$$

- The mean dry point

$$\bar{N}_o = 18640$$

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By assuming that the populations making up these means are uniform
and that concrete behaves identically in the grooved and non-grooved state:

$$\sigma_{De}^2 = \frac{20,079}{135} = 148: \quad \sigma_{De} = 12 \text{ cps/10 s} \quad \Delta h_I \text{ 0.032 m (sic)}$$

	N_0 cps/10 λ	t_0 unity 30s	ϕ'	$N_0 + I$ cps/10 λ	t_I unity 10s
POINT No 1 (G)	18 584	10	45	18 751	60
(G) 2	18599	10	45	18 741	25
(G) 3	18685	50	18	18 713	46
(G) 4	18761	50	19	18 819	50
(NG) 5	18673	10	45	18753	30
(NG) 6	18674	50	19	18810	50
(NG) 7	18578	50	19	18992	50
(NG) 8	18686	55	18	18841	55

t_0 = Computational time for determination of N_0

t_I = Computational time for determination of $(I + N_0)$

(continued)

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σ''	I cps / μs	\sqrt{I}	$\frac{D}{\lambda I}$ mm	Computational error $\Delta h_{I=2\sigma}^2$ in mm
18	167	47	0,22	$\pm 0,12$
27,5	202	51	0,27	$\pm 0,14$
20	32	26	0,04	$\pm 0,06$
20	58	27	0,08	$\pm 0,07$
25	90	50	0,12	$\pm 0,13$
19	166	28	0,22	$\pm 0,07$
20	414	27	0,35	$\pm 0,07$
16	153	25	0,20	$\pm 0,07$

t_o = Computational time for determination of N_o

t_I = Computational time for determination of $(I + N_o)$

$$\begin{array}{llll}
\sigma_{IR}^2 \frac{18\ 750}{220} = 85 & \sigma_{IR} : 9 \text{ cps/10s} & \Delta h = 0.01 \text{ mm} & \underline{/78} \\
\sigma_{INR}^2 \frac{18\ 850}{220} = 85 & \sigma_{INR} : 9 \text{ cps/10s} & \Delta h = 0.01 \text{ mm} & \\
\sigma_{N_o}^2 \frac{18\ 640}{160} = 1 & \sigma_{N_o} : 10 \text{ cps/10s} & &
\end{array}$$

Thus, by assuming that the equilibriums are well established and that each experiment at one point of a grooved concrete (for example) could be compared to the repetition of another experiment with grooved concrete, the accuracy with horizontal straight lines representing the holdings at equilibrium and residual water values are, from the computational viewpoint, 0.03 and 0.01 mm respectively.

NORMALIZATION OF MEANS $\overline{N'}$ AND $\overline{N'-I}$

TIME	GROOVED CONCRETE	
in	$\overline{N'} = 1438 \text{ dyn/100 cm}^2$ stab	$(\overline{N'-I}) = 1221 \text{ dyn/100 cm}^2$ stab
seconds	$\overline{N'} / \overline{N'}_{\text{stab}}$	$(\overline{N'-I}) / (\overline{N'-I})_{\text{stab}}$
0	1,000	1,000
50	9,991	9,994
150	794	796
250	582	586
350	277	282
450	251	24
550	119	54
650	70	32
750	114	37
850	86	5
950	60	1
1050	58	3
1150	119	60
1250	58	20
1350	32	7
1450	24	27
1550		
1650		
1750		
1850		
1950		

ANNEX IV (cont.)

NORMALIZATION OF MEANS $\overline{N'}$ AND $\overline{N'-I}$

Time in seconds	NON - GROOVED CONCRETE	
	$\overline{N'}$	$\overline{N'-I}$
0	1.000	1.000
50	0.992	0.990
150	.988	.984
250	.981	.978
350	.972	.968
450	.963	.958
550	.950	.945
650	.937	.932
750	.920	.916
850	.901	.897
950	.882	.878
1050	.863	.859
1150	.843	.840
1250	.823	.820
1350	.803	.800
1450	.783	.780
1550	.763	.760
1650	.743	.740
1750	.724	.720
1850	.704	.700
1950	.684	.680

Drainage functions

According to figure 24 the recession can be described in some domains by a straight line with logarithmic coordinates. It therefore follows:

$$(1) \quad \bar{H}_r = at^{-b} \quad \begin{array}{l} H_r \text{ in subdimensional unity} \\ t \text{ in seconds} \end{array}$$

It is enough to write that straight lines D_1 , D_2 , D_3 each pass through two points respectively:

A and C	for	D_1	(non-grooved)
C and E	for	D_2	(non-grooved)
B and F	for	D_3	(grooved)

and to solve the three systems of two equations with two unknowns. It follows that:

$$\begin{array}{lll} a_1 = 4.902 & a_2 = 3.083 \cdot 10^3 & a_3 = 5.264 \cdot 10^8 \\ b_1 = 0.41944 & b_2 = 1.51952 & b_3 = 3.7360 \end{array}$$

Note that $\bar{H}_r = \frac{D-I}{De-I}$ and the rule of type (1) relative to the straight line De can be compared to the recession curves of Izzard (1946).

Note likewise that it should be possible to produce an expression of the fluid rate at the edge. Indeed, there is delivery q given by

$$(2) \quad q = uh$$

in which u is the mean rate in the sheet of water with thickness h at a point located on the edge. Now, it is known (page __, formula 5) that the delivery is most likely provided by a rule similar to (1) or:

$$(3) \quad q = A_1 t - B_1$$

and that (1) may be expressed at the same time resorting to the present notations with h by

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$$(4) \quad h = A_2 t^{-B_2}$$

From equation (2) there is derived:

$$u = \frac{q}{H} = \frac{A_1}{A_2} t^{-(B-B_2)}$$

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